Final Report

TRACTOR TRAILER COASTDOWN &
COMPUTATIONAL FLUID DYNAMICS COMPARISON TEST

Evaluation of SmartTruck's TopKit Trailer System

Addendum: Data Reduction Using Method 0 (no airspeed correction and constant Crr)

Conducted by SmartTruck Systems:

Greenville, SC 29605

July 30, 2014

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1 Background and Introduction

SmartTruck is pleased to submit the following application for our TopKit Trailer System to EPA's SmartWay Transport Partnership program for verification.

Figure 1 - SmartTruck TopKit System

The TopKit Trailer System is a *trailer aerodynamic technology* as defined by EPA's program and was designed and developed by SmartTruck Systems located in Greenville, SC. As shown in Figure 1 - SmartTruck TopKit System, the TopKit is an integrated set of components that work as a system to reduce drag. The components of the TopKit are:

A. Aerodynamic Side Fairings (2).

B. Aerodynamic Rain Guard (ARG).

Additional photos and images of the TopKit are shown in Appendix A – Photos and Images.

To develop the TopKit, SmartTruck used the same advanced aerospace engineering tools that are currently used in the highest levels of the commercial aviation and space program industries. Specifically, SmartTruck designs and initially assesses aerodynamic performance using NASA's Fully Unstructured Navier-Stokes 3D Computational Fluid Dynamics (CFD) model and solver along with CD-ADAPCO's Navier-Stokes 3D Computational Fluid Dynamics (CFD) model and solver. The computational resources needed to resolve the tremendous grid sizes and detailed air flow characteristics associated with today's Class 8 vehicles were provided to SmartTruck by NICS, The National Institute for Computer Sciences, located at Oak Ridge National Laboratory. NICS has provided SmartTruck the use of their Kraken system, a Cray XT5 supercomputer.

	Avg. CD Method 0	% CD Decrease	% MPG Increase (65 MPH)
Baseline	0.7595	N/A	N/A
TopKit	0.70153	7.63%	5.62%

Table 1 - Summary of CFD Results

As with our previous designs, once SmartTruck has completed our aerodynamic assessments with CFD, SmartTruck makes final changes and validates the performance of the TopKit by conducting state of the art coastdown testing. This process started with an evaluation [redacted] The 72" version was selected to maximize performance while avoiding mounting issues with exterior rub rails. SmartTruck's assessment of the TopKit Trailer System shows that installing the TopKit System on today's aerodynamic Class 8 long haul tractor trailer reduces drag by 7.63%. The fuel efficiency improvement, at steady state 65 MPH, associated with a 7.63% reduction in drag translates to approximately 5.62% improvement. [redacted]

The primary reason for this coastdown testing program is to achieve EPA SmartWay Transport Program verification for the TopKit Trailer System. However, SmartTruck has gone above and beyond the standard testing protocol by outfitting our testing vehicle with a state of the art data acquisition system. This system has almost 800 potential channels to monitor and record a wide variety of vehicle systems and effects, including true air speed, wheel speed, gps speed, wind direction, steering input and any/all data gathered through the vehicle's engine bus.

Coastdown testing on the TopKit System was conducted April 17th, 2014 at Michelin's Laurens Proving Grounds in Laurens, South Carolina. Test results using the Test Run to Baseline Run comparison conclude the TopKit Trailer System produces a 5.62% improvement in fuel efficiency at 65 MPH.

2 Coastdown Testing

2.1 Approach

SmartTruck Systems' testing program was done in accordance with proven coastdown testing techniques. To further facilitate proper scientific protocol, a consistent 2011 Wabash 53 foot dry van trailer, provided by XTRA Lease Trailer Rentals, and Navistar 2010 model year ProStar Tractor was used. This combination remained consistent throughout testing.

The test truck was equipped with state of the art data acquisition systems. These systems have almost 800 potential channels to monitor and record a wide variety of vehicle systems and effects, including, but not limited to:

- True air speed via pitot static tube
- [redacted]
- GPS speed
- Engine rpm
- Yaw angle/wind direction
- Steering input
- Engine fan RPM

Weather was monitored by a Davis Vantage Vue weather station, located next to the track, to provide data as close to what the truck was exposed to as possible.

2.2 Test Protocol

2.2.1 Discussion of Coastdown Testing For Heavy Vehicles

EPA's Modified Protocol based on SAE J2263 coastdown protocol has been suggested for testing of Class 8 trucks to qualify aerodynamic devices on the tractor and the trailer. Our experience has been, after testing more than 200 different aerodynamic configurations and over 700 individual test runs, is that there are several issues with the suggested protocol which make it virtually impossible to achieve accurate results and very difficult and expensive to perform the testing.

2.2.2 SAE J2263 Protocol Issues in Heavy Truck Testing

2.2.2.1 Issue 1 – 70 mph to 17 mph Coastdown Interval

This coastdown interval is required for the data reduction technique spelled out in the protocol to work accurately (i.e. obtaining the zero velocity drag force for rolling resistance correction). The J2263 protocol was developed for light vehicles (basically automobiles and light trucks) that could accelerate to 70 mph and then coastdown to less than 17 mph in a reasonable distance (about 6,000 feet) due to high drag to weight ratio typical of cars and light trucks. There are many facilities that are available that are long enough for this test with cars and light trucks. However, a Class 8 tractor-trailer combination, completely unloaded, weighs in the order of 36,000 pounds. It's power to weight and drag to weight is a fraction of a car or light truck. Consequently the total distance required to perform the SAE J2263 coastdown is typically 13,000+ feet. See Figure 2 - Calibrated Truck Model Result.

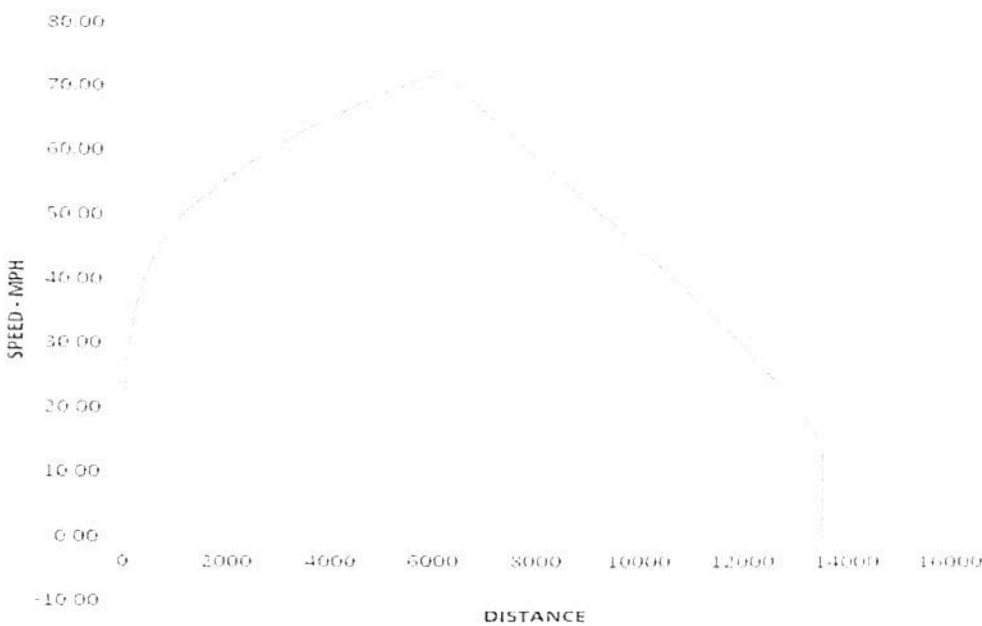


Figure 2 - Calibrated Truck Model Result

Not many facilities offer this size track. SmartTruck has a Space Act agreement with NASA to use their Space Shuttle runway (which is 18,000 feet in length) and we have tested there using a coastdown of 70 mph to less than 15 mph on several occasions. The Shuttle runway is active and has heightened security so scheduling and operations are quite difficult. Our experience is that this is a very expensive facility that few would take advantage of, yet the J2263 protocol, as currently written, will require this type of venue.

2.2.2.2 Issue 2 – Assumption That the Rolling Resistance and Friction Is Constant i.e. Does Not Vary With Speed

Rolling resistance (and friction) is accounted for in the SAE J2263 protocol by plotting the instantaneous total force calculated from the measured dV/dT and vehicle weight versus velocity and then extrapolating it to zero speed. Since the aerodynamic drag is zero at zero speed, the intersection represents the rolling resistance and friction forces at zero speed. This force is then subtracted from the total force to extract aerodynamic drag at the desired speed. Figure 3 below is a typical curve of this sort from one of SmartTruck's tests at the Kennedy Space Center.

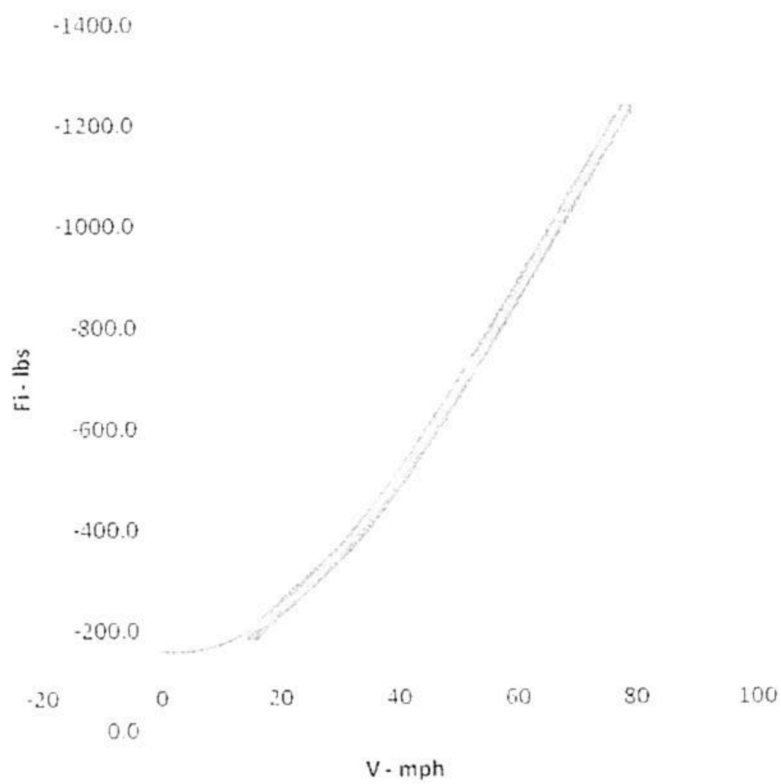


Figure 3

As can be seen the intercept with the y axis is at a retarding force of 159 pounds. This divided by the weight gives a coefficient of rolling resistance (Crr) of 0.0044. This is consistent with our experience with the tires used on our test trailer at zero speed. However, if one uses data on Crr from the tire companies and literature one finds out that Crr varies as the square of speed. Indeed our data for the tires we use and other data on other test tires suggest that the coefficient of rolling resistance follows the following formula:

$$Crr = Crr_o + (5x10^{-7}) * V^2$$

When this formula is used for data reduction a much more accurate drag prediction results because, in fact, the rolling resistance and friction drag are not constant and the difference in rolling resistance at speed and the zero speed value gets added to the "aerodynamic" drag value. Figure 4 below is again from our Kennedy testing and shows the difference in the drag prediction when Crr is constant and when the formula above is used.

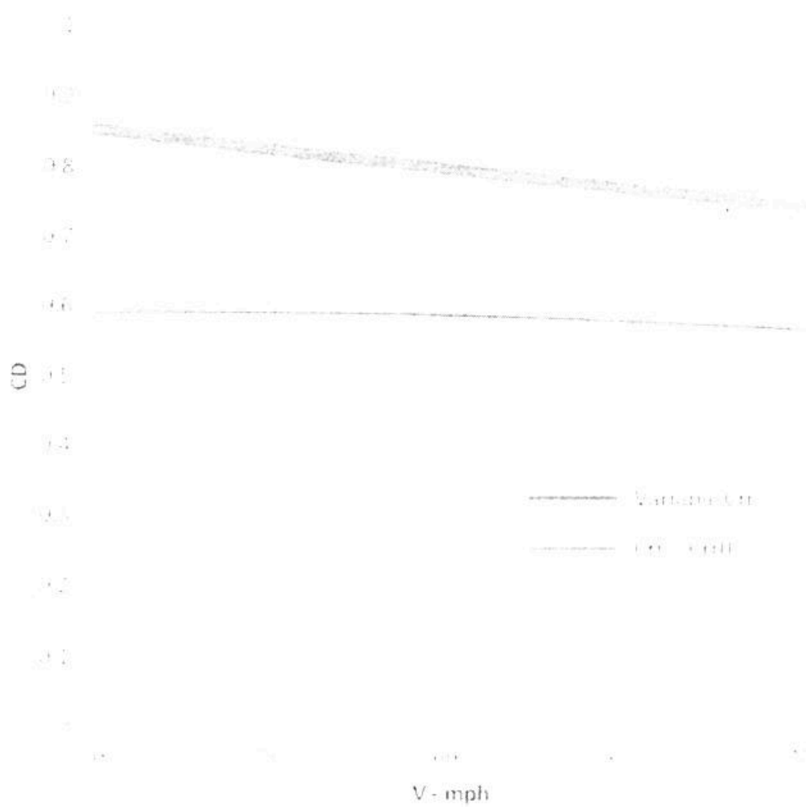


Figure 4

The red line is the Cd predicted using the variable Crr while the blue line is the Cd predicted using the constant value of $Crr=Crr_o$.

The red line is nearly constant with speed and very closely agrees with the CFD predicted value of Cd as well as the Cd implied by our fuel mileage testing of this configuration. The Cd predicted by the SAE J2263 protocol is high, due to the infusion of rolling resistance and friction drag in the aerodynamic drag levels, and significantly variant with speed which is inconsistent with any other analysis of drag. Errors in the relative drag levels using the SAE J2263 are of course smaller than the absolute level error but still can be significant since the Crr error is constant. As the aerodynamic drag is reduced the Crr error is a larger percent of the total predicted drag level thus increasing the Cd level relative to a higher drag baseline. Using a varying Crr is not perfect but errors in the Crr slope represent much smaller differential errors than just assuming the slope is zero.

Again, light vehicles get away with this because of their higher aero drag to rolling resistance ratio due to their lighter weight. In heavy vehicles the error is too great.

2.2.3 The SmartTruck Heavy Vehicle Coastdown Test Protocol

Simply stated, the SmartTruck protocol uses a combination of high speed test runs with coastdown from 65 mph to 40 mph and low speed test runs coasting from 25 mph to 0 mph to obtain the required high speed drag data and the value Crr_o with which to correct the total drag. Figure 5 – Simulated Coastdown Distance below shows that the accelerate-coastdown distance for the high speed coastdown is just over 6,000 feet and the coastdown portion required is just under 4,000 feet for a vehicle weight of 36,500 lbs.

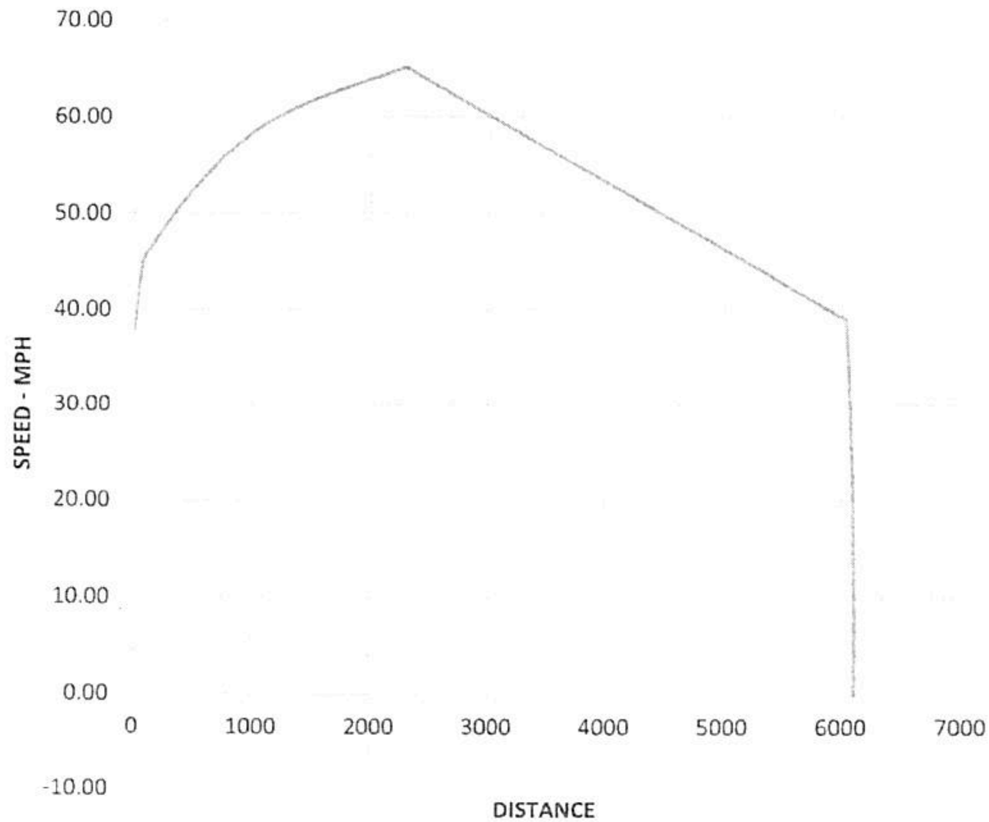


Figure 5 – Simulated Coastdown Distance

There are many facilities available with this length and adequate turn around tracks. SmartTruck has tested at Michelin's Laurens Proving Grounds Track 9 (available for rent to the public) and an inactive runway at the South Carolina Technical Aviation Center (SCTAC) in Greenville to perform these tests. This allows local, cost effective testing to be done on many configurations. Figure 6 - Low Speed Lap, Figure 7 - High Speed Laps and Figure 8 - High Speed Laps below shows actual raw data from the SmartTruck data system for a single configuration run.

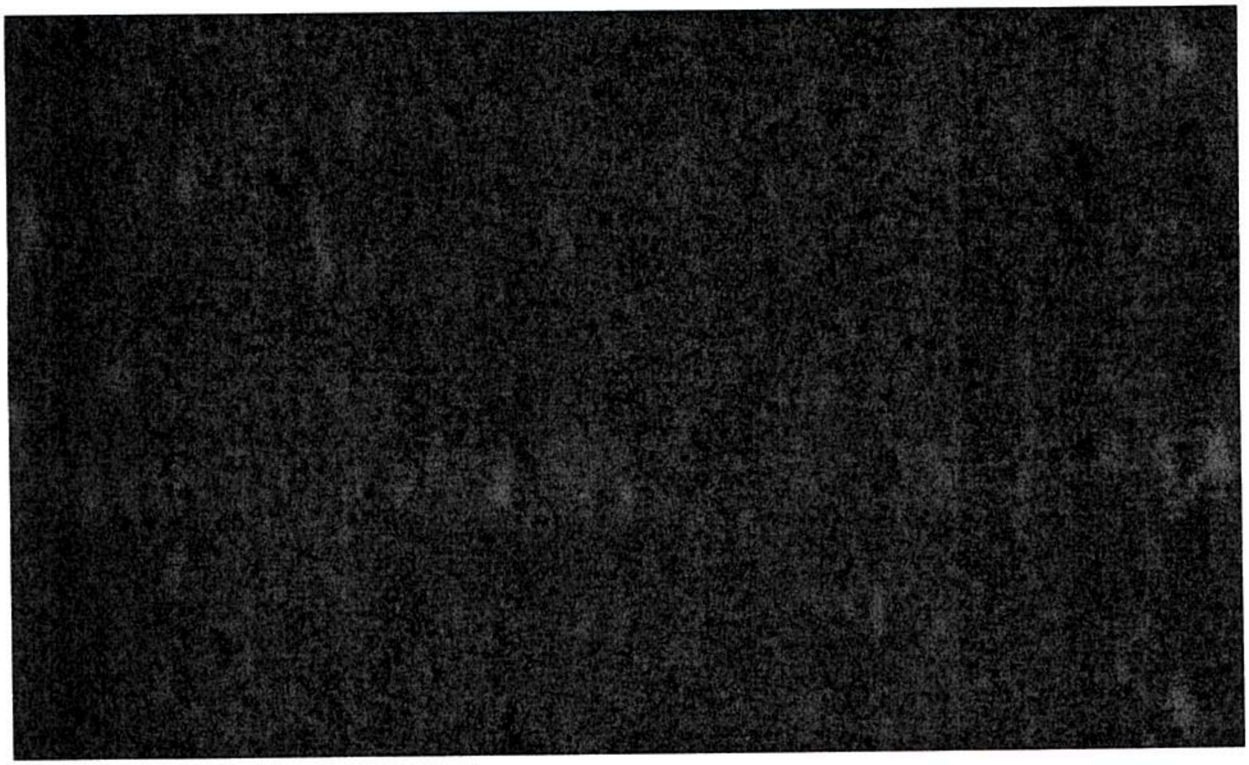


Figure 6 - Low Speed Lap

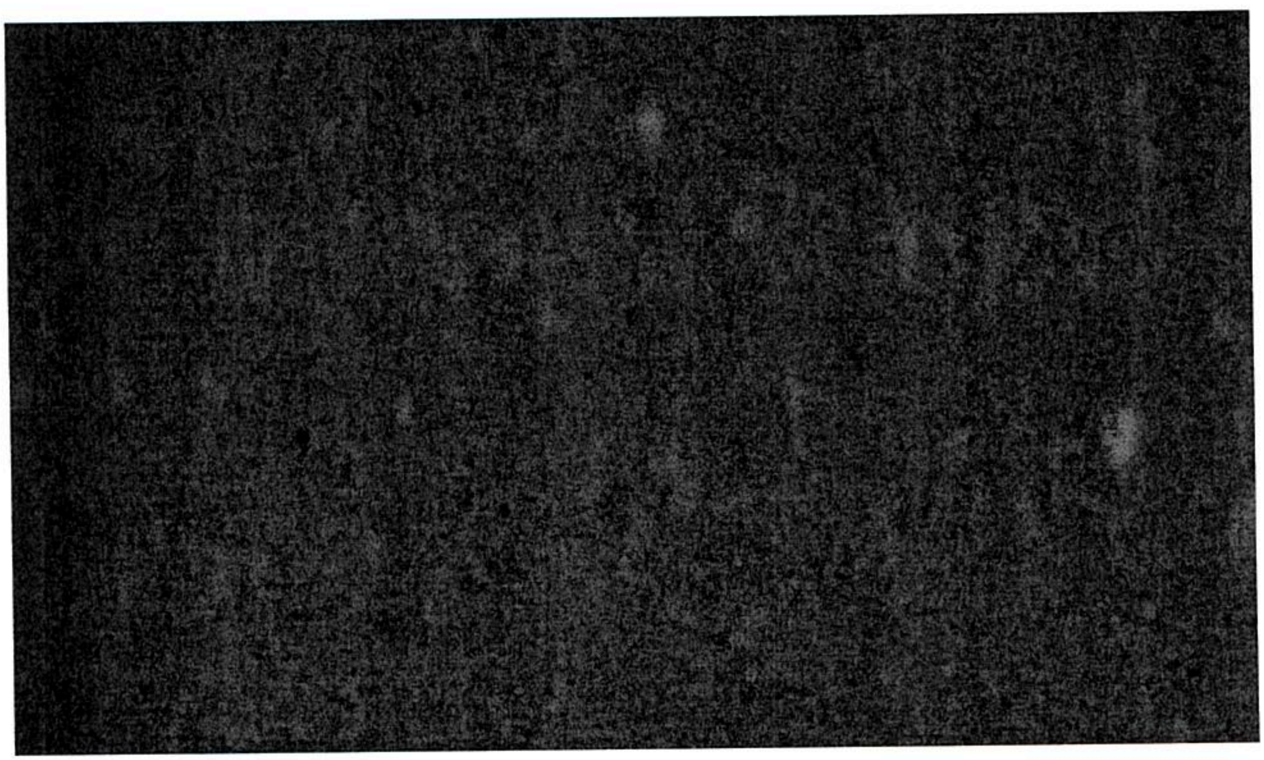


Figure 7 - High Speed Laps

[redacted]

Figure 8 - High Speed Laps

The first lines are the truck airspeed data from a calibrated pitot static system on board the tractor. The second lines are from a highly accurate GPS sensor and the third lines are the vehicle speed measured with [redacted] While the airspeed system is not strictly needed for good Cd measurement as long as the winds are low and consistent, it is needed to measure the time variant Cd during any given run. SmartTruck uses the time variant Cd to get average Cd, and to see if our aerodynamic modifications reduces or increases the frequency or magnitude of Cd variations. We also use the airspeed system data to disqualify a run with excessive gusting or yaw within in a run. We measure the yaw angle with our data system directly but again this is not strictly necessary for good average Cd data if a good weather station is used as is required by both protocols. Airspeed data contains a significant high frequency content that is related to cab vibration not gusting. This must be removed from the data to obtain good time variant Cd information. The chart below, Figure 9, shows the raw signal, blue, and the filtered signal, red, that is ultimately used in the calculations.

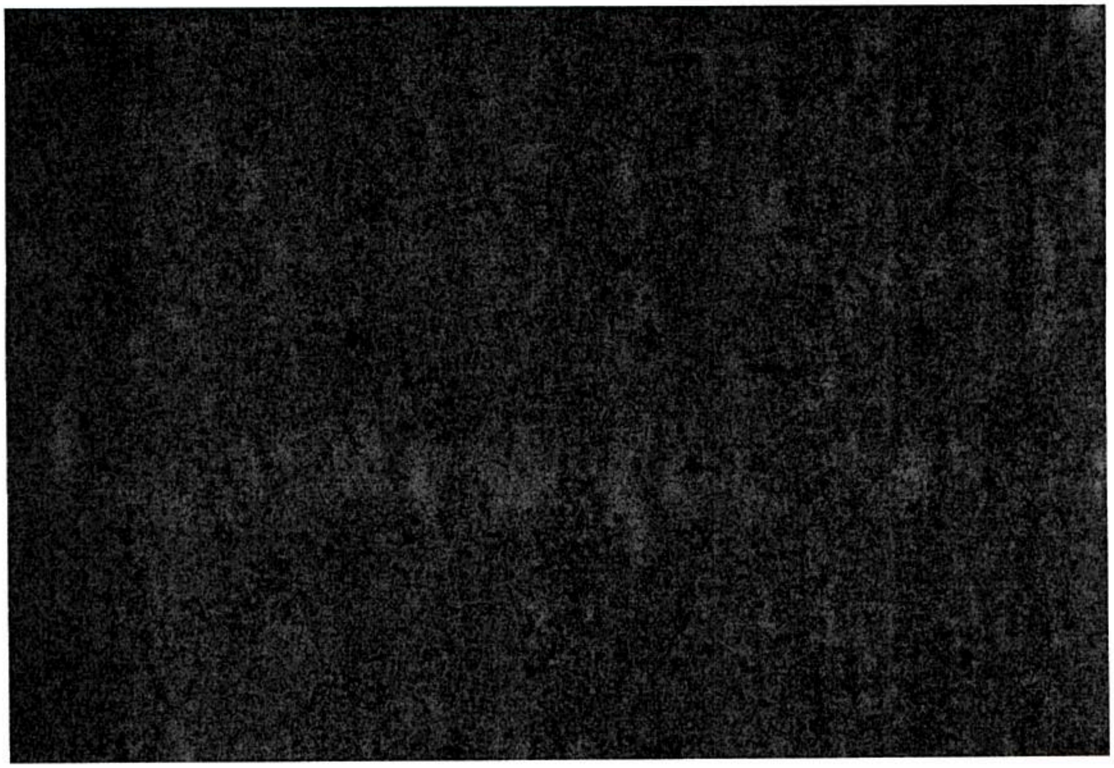


Figure 9

Figure 10 - Low Speed Run Results show results of the analysis of the low speed runs used to obtain Crr for removal of the rolling resistance and friction from the total retarding force to get the aerodynamic drag force.

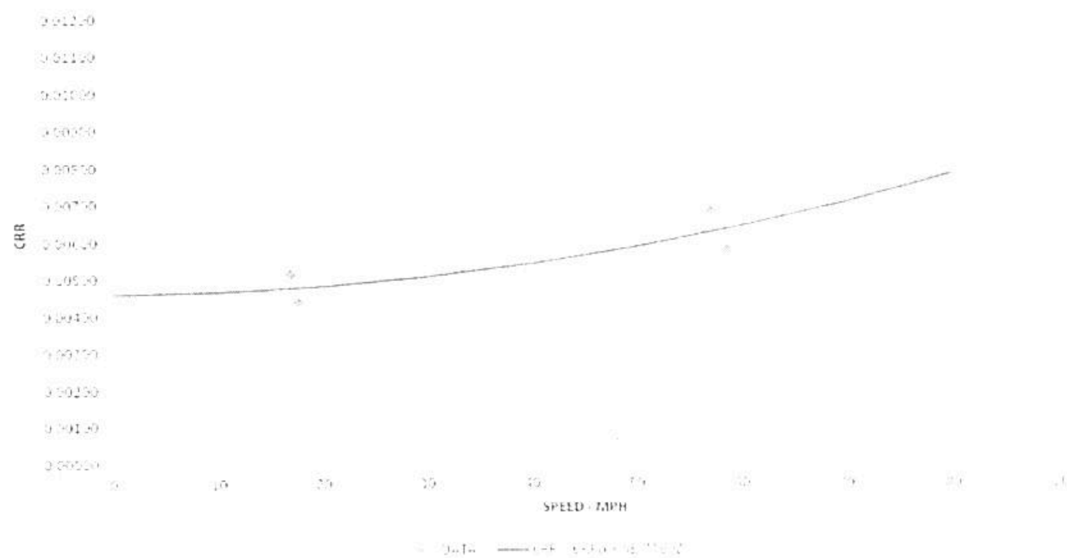


Figure 10 - Low Speed Run Results

Figure 11 – CD (Method 0) vs Time Baseline and TopKit Compared shows Cd vs. time data for both Baseline and TopKit on one of our Track 9 test runs.

[redacted]

Figure 11 – CD (Method 0) vs Time Baseline and TopKit Compared

The blue line is the time accurate Cd, while the red line is the average Cd.

To obtain a final Cd value, SmartTruck averages all Cds from each individual run for the configuration. Average Cds are also checked for too great a run to run variance in which case that run is eliminated and repeated.

SmartTruck has tested over 200 configurations on over 700 runs using this protocol. We test our baseline configuration at every test and several times during a test day and consistently get accurate and repeatable results both within a test day and between tests going back over two years.

2.3 Test Procedure

[redacted] After the test run is completed, [redacted]

[redacted] This method allows for more accurate correction of high speed aerodynamic signals from low speed rolling resistance.

[redacted] By doing this, [redacted] As a secondary data check, [redacted]

After each run a pit stop is preformed, where engineers will:

- Download SoMat data acquisition system data.
- Review of coastdown data to ensure integrity.
- Check steer tire pressures.
- A tractor check list is performed to ensure it was still in proper working condition.
- All aerodynamic parts are checked to ensure proper working functionality.
- Weather station data is downloaded and checked to ensure good weather conditions.

2.4 Vehicle Preparation

- All vehicle axles were aligned to manufacturer's specifications. Tractor and trailer axle bearing and brake adjustments were made at this time.
- The tractor trailer gap was set in a commonly used long haul configuration. Specifically, the King Pin location was set so that the back of the cab to the front of the trailer gap was [redacted]
- The rear trailer slider was set to the California standard of 40 feet.
- The main fuel tanks were [redacted]
- Documentation of the test vehicle configuration and proper installation of the TopKit components were completed prior to each test.

- The same fuel from the same source was used throughout the entire test procedure. And a [redacted] was used ensure an accurate [redacted]

2.5 Pre-test Inspection

Each test day before vehicle warm-up, the vehicles were run for brief periods and checked to ensure they were in good working order. The tire pressures were checked to ensure proper inflation. [redacted] was used ensure an [redacted]

2.6 Warm-up

Prior to each testing day the truck is operated on the track for a one hour warm-up [redacted]

2.7 Aerodynamic Kit Changes

Kit changes are a periodic part of coastdown testing. SmartTruck Systems [redacted] For the most consistent scientific results, this procedure is followed regardless if there is an aerodynamic kit change or not. However, if an aerodynamic kit change [redacted] a warm-up must be performed again.

2.8 Vehicle Weight

Fuel consumption for each vehicle was measured for each run completed. Consumption, measured in pounds, was determined by reading the total fuel used from the engine data and calculating the difference from the previous run. Weight for each kit configuration was also accounted for.

2.9 *Vehicle and Equipment Specifications*

	Tractor	Trailer
Unit #	USDOT 497152	U94355
Make	Navistar	Wabash
Model	Pro Star	N/A
V.I.N.	3HSDJSJR7BN409752	1JJV532D5CL726150
Engine	Navistar Maxforce	N/A
Odometer	284,779	N/A
Tires-Steer	Michelin X Green 275/80R22.5	N/A
Tires-Drive/Trailer	Michelin X Line Energy D 275/80R22.5	Michelin X Line Energy 275/80R22.5
Manufacture Year	2010	2011

Table 2 – Tractor, Trailer Information

Purpose	Sensor	Type	Capacity
DAQ	SoMat eDAQlite	Rugged Data Recorder	Analog, Strain Gage, Thermocouple, Digital I/O, Pulse Counter, GPS, Vehicle Bus
Steering	Celesco SG1-80-3	Potentiometer	Essentially Infinite Resolution
Fan RPM	Monarch Remote Optical Sensor	Optical Sensor	1-250,000 RPM
Pitot	Senserion SDP2000L	Low Range Differential Pressure Transducer	0.0-0.5 PSI, Temperature Compensated
Windvane	World Encoders SR12-512A/12-30	Absolute Shaft Encoder	512 (9bit) Resolution
5th Wheel	ACCU-Coder 25T-425G-1200NV1QOC-9D	Video Encoder	1200 Counts Per Revolution
GPS	Garmin GPS18x-5Hz	GPS Sensor	5Hz Measurement Pulse Output, 0.2 second increments of UTC time

Table 3 - Instrumentation Information

2.10 *Description of Test Facility*

Testing was conducted in Laurens, South Carolina at Michelin's Laurens Proving Grounds (LPG). LPG is a state of the art testing facility with a total of nine unique tracks including: a main test track, road course, wet handling, gravel endurance, off road inclines, heavy truck loop, noise, vehicle dynamics and drift/pull.

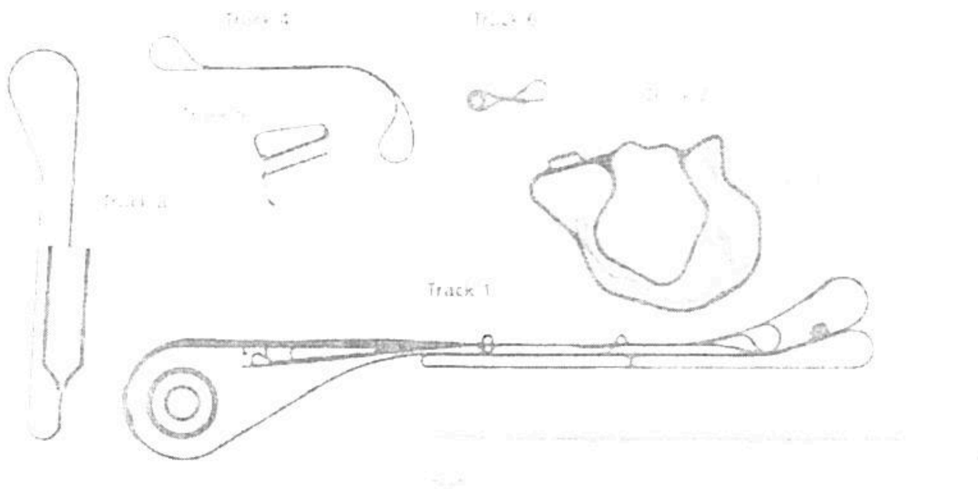


Figure 12- LPG Facility Map

SmartTruck currently takes advantage of LPG's Track 9, Drift/Pull. This track is a 4,800 foot straightaway with turnaround loops on either end for a total length of 1.25 miles. The track width is 40 feet in the turnarounds and 80 feet in the straightaway. The surface of the track is asphalt with a surface texture (Macro/Micro) of smooth/rough. Track 9 also has a near perfect flatness over the straightaway length with an International Roughness Index (IRI) of 37.4 in/mile.

Figure 13 - Track 9, Drift/Pull

2.11 Calculation Equations

2.11.1 Rolling Resistance

Rolling resistance at zero speed was measured for each configuration from the low speed runs and the actual RR curve was:

$$Crr = Crr_o \quad \text{(Method 0)}$$

Where:

Crr is the coefficient of rolling resistance
Crr_0 is the coefficient of rolling resistance at zero speed

This was done for each configuration.

2.11.2 Drag Calculation Equations (Method 0)

$$D_{aero} = \left(\frac{W_c}{g}\right) * \left(\frac{dV_{wheelspeed}}{dT}\right) - Crr_o * W$$

$$Cd = \frac{D_{aero}}{A_{ref}/(0.5 * \rho * V_{wheelspeed}^2)}$$

Where:

W_c is vehicle weight in lbs. (which includes the inertial effects of the wheels)
g is the gravitational constant, 32.2 ft/ sec^2
W is vehicle weight in lbs.
A_{ref} is the reference area of the vehicle, 97.2 ft^2
ρ is measured air density in (slug - ft)/sec^2
$V_{wheelspeed}$ is the measured vehicle speed in ft/sec
Crr_0 is the coefficient of rolling resistance at zero speed

2.12 Test Configuration

Following the conclusion of all baseline testing and calculations, the test truck was outfitted with the TopKit Trailer System. This configuration consists of:

A. Aerodynamic Side Fairings (2).
B. Aerodynamic Rain Guard (ARG).

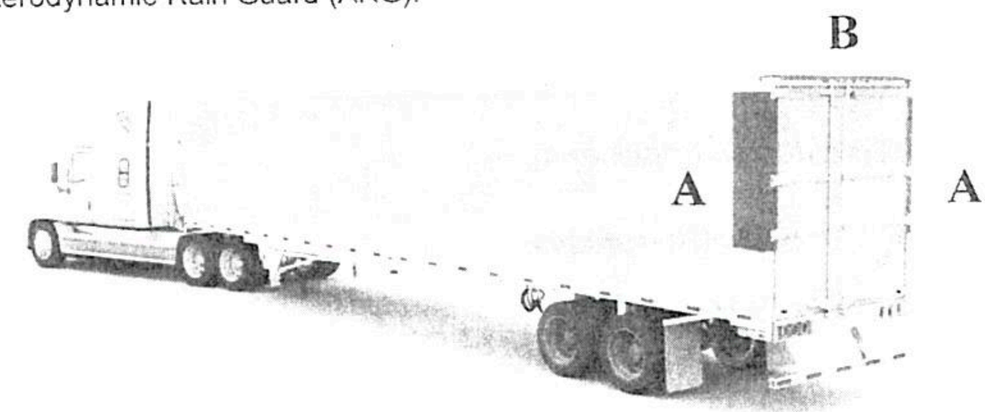


Figure 14 - Rear View of Aerodynamic Side Fairings and Aerodynamic Rain Gutter

3 Computational Fluid Dynamics (CFD)

3.1 CFD Approach

SmartTruck first validated the TopKit by [redacted] needed to achieve MPG improvement greater than 5%. Because CFD predicted greater than 5% with [redacted]

3.2 Computer Systems and Software

CD-Adapco's Star-CCM+ v8.02 software was used for gridding and computations. Post Processing was performed by both Tecplot360 as well as Star-CCM+.

All grids were pre and post processed on an internal machine outfitted with a 3.20GHz Intel i7 Processor with 12 cores and 64GB of RAM.

All computational runs were performed on The National Institute for Computational Sciences (NICS) super computer Kraken XT5. Kraken is composed of 112,896 compute cores (two 2.6GHz six-core AMD Opteron processors per node) and 147TB of compute memory (16GB of memory per node). Kraken has a peak performance of 1.17 PetaFLOP. More information about NICS and the Kraken supercomputer can be found at: http://www.nics.tennessee.edu/computing-resources/kraken.

3.3 Testing Method

All runs consisted of a half model, steady state analysis utilizing SmartTruck Systems (STS) gridding version 9. Rotating vehicle tires and a moving floor were also used.

Grid Type	[redacted]
Flow Solver	Navier Stokes [redacted]
Number of Prism Layers, Critical Flow Areas	[redacted]
Boundary Layer First Cell Size (mm)	
Total Number of Cells:	
Baseline	[redacted]
3 PIECE TopKit	

Far Field Boundaries:	
For/Aft (m)	[redacted]
Side/Side (m)	[redacted]
Above/Below (m)	[redacted]
Boundary Conditions:	
Tires	Rotating Tire to Match Vehicle Speed
Ground	Moving Viscous Floor to Match Vehicle Speed
Free-Stream	Fully Viscous Solution
Wall Treatment	[redacted]
Air Speed (m/s)	29.0576
Density (kg/m³)	[redacted]
Reference Pressure (Pa)	[redacted]
Frontal Area (m²)	[redacted]
Turbulence Model	[redacted]
Turbulent Viscosity Ratio	[redacted]

Table 4 - CFD Parameters

3.4 Test Configuration

SmartTruck System's TopKit Trailer System consists of:

A. Aerodynamic Side Fairings (2).

B. Aerodynamic Rain Guard (ARG).

4 Test Data

4.1 Coastdown Testing

4.1.1 Baseline Segment (Method 0)

Aero Kit	Run	Crr0	CD	Avg. Temp	Avg. Wind	Air Density	Vehicle Weight	Avg. Steer Tire Pressure	Time
				deg. F	MPH	slug/ft^3	lbs.	PSI	Eastern
[redacted]									

Table 5 - Baseline Test Data

Table 5 - Baseline Test Data shows the test data from the baseline segments. [redacted]

Therefore, using Method 0, the average Drag Coefficient number of 0.7595 was found to be accurate for the baseline and used in comparison to the TopKit.

	Avg. CD	% CD Decrease	% MPG Increase
Baseline	0.7595	N/A	N/A

Table 6 – Baseline Performance Summary

[redacted]

Aero Kit	Run	Crr₀	CD	Avg. Temp	Avg. Wind	Air Density	Vehicle Weight	Avg. Steer Tire Pressure	Time
				deg. F	MPH	slug/ft^3	lbs.	PSI	Eastern
[redacted]									

Table 7 – Aerodynamic TopKit Test Data

Table 7 – Aerodynamic TopKit Test Data shows the test data from the TopKit segments. Compared to the Baseline coastdown test, the average percent drag coefficient change was 7.63% which equates to 5.62% improvement in MPG at 65 MPH. The TopKit's average Drag Coefficient number was found to be 0.70153.

	Avg. CD Method 0	% CD Decrease	% MPG Increase (65 MPH)
TopKit	0.70153	7.63%	5.62%

Table 8 - TopKit Performance Summary

4.2 Computational Fluid Dynamics (CFD)

SmartTruck System's TopKit was found to have a 9.07% improvement in drag.

	TopKit	Baseline	Difference
TRACTOR	0.333259	0.332230	0.001029
TRAILER	0.161495	0.211871	-0.050376
VEHICLE TOTAL	0.494754	0.544101	-0.049347
% DECREASE IN DRAG	9.07%		
% INCREASE IN MPG	6.06%		

Table 9 – CFD Results

A 9.07% improvement in drag results in a 6.06% improvement in highway MPG (at 65 mph). Raw data can be found in Appendix C – Computational Fluid Dynamics Data.

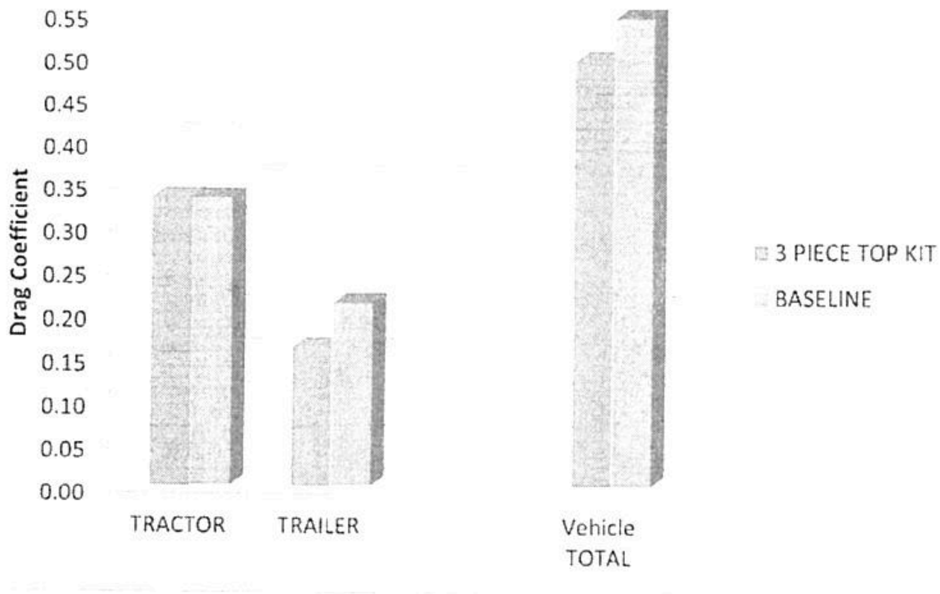


Figure 15 - Drag Coefficient Data

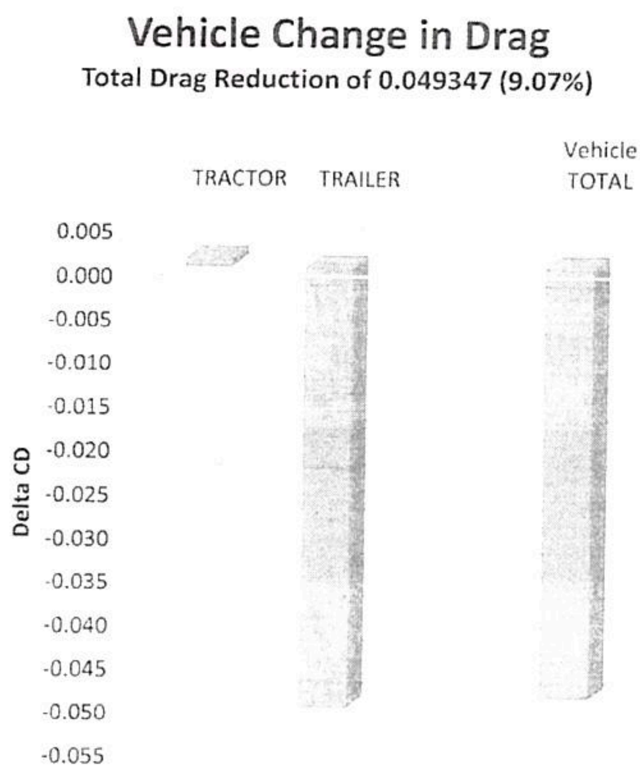


Figure 16 – Total Vehicle Change in CD

[redacted]

[redacted]

5 Summary of Results

5.1 *Coastdown*

	Avg. CD	% CD Decrease	% MPG Increase (65 MPH)
Baseline	0.7595	N/A	N/A
TopKit	0.70153	7.63%	5.62%

Table 10 - Summary of Coastdown Results

[redacted]

5.2 *CFD*

	Avg. CD	% CD Decrease	% MPG Increase (65 MPH)
Baseline	0.544101	N/A	N/A
TopKit	0.494754	9.07%	6.06%

Table 12 - Summary of CFD Results

6 Conclusion

The testing and data calculation protocols described in this document conclude that:

On today's most aerodynamic tractor trailer configurations, SmartTruck's TopKit System produces a 5.62% fuel efficiency improvement.

The TopKit System is expected to have slightly different performance with different types of trailers and tractors due to the differences in the aerodynamic performance of the base trailer and/or tractor. Additionally, different types of trailer and tractor components will also have a slight impact on the performance of the TopKit.

Preparation and Approval

Report Prepared By

Date 7-30-2018

Nate See

Lead Test Engineer SmartTruck Systems

Report Approved By

Date 7-30-18

Steve Wulff

Chief Operations Officer SmartTruck Systems

Appendix A – Photos and Images

Images of the TopKit Trailer System

Figure 18 - Rear View of TopKit

Figure 19 - Side View of TopKit

Testing Equipment

[redacted]

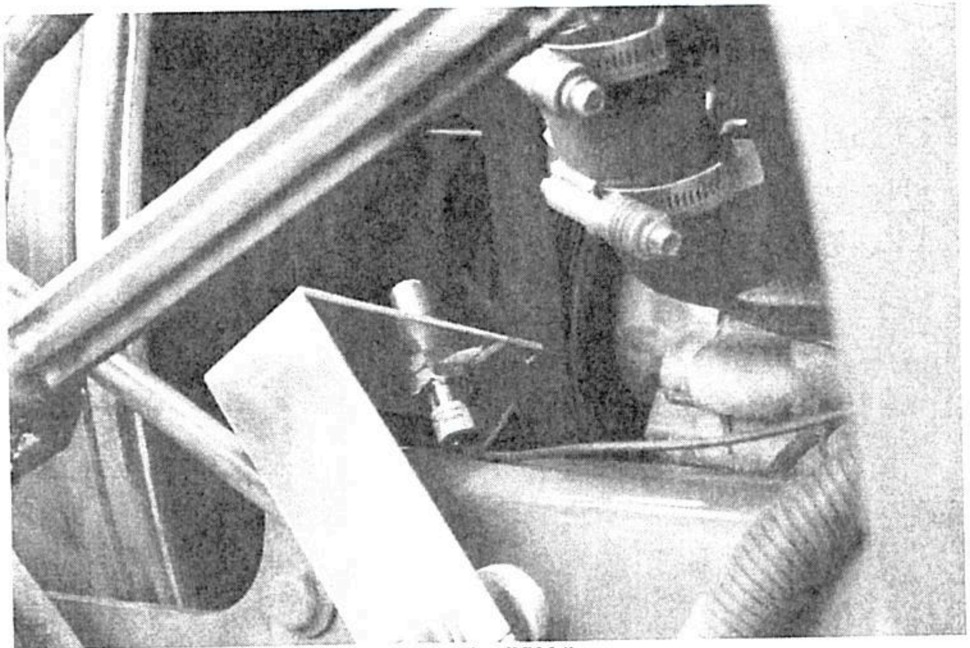


Figure 22 - Fan RPM Sensor

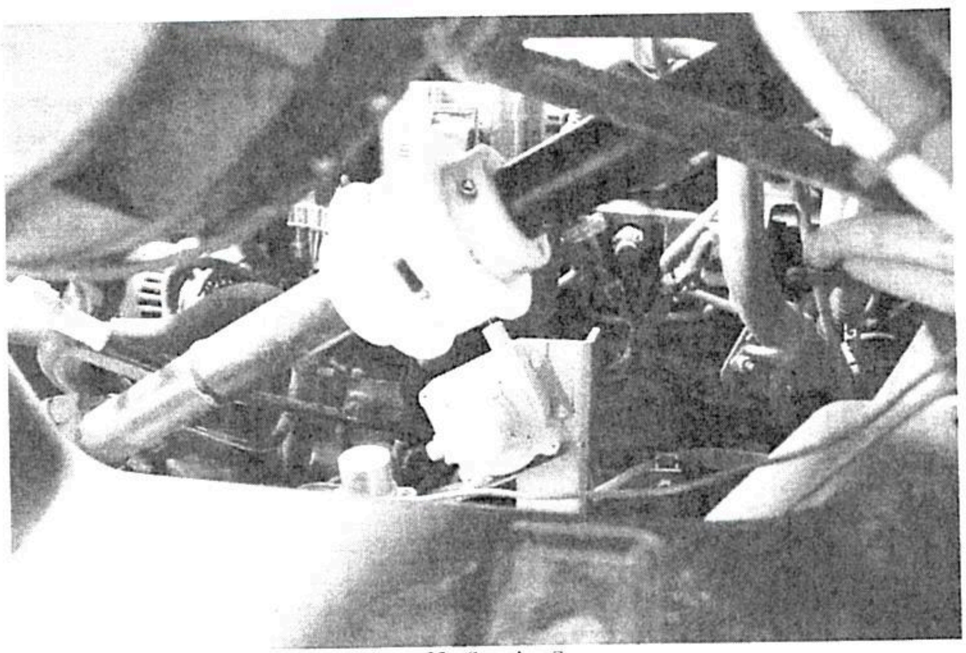


Figure 23 - Steering Sensor

Appendix B – Coastdown Plots

[redacted]

Figure 24 - TopKit Performances

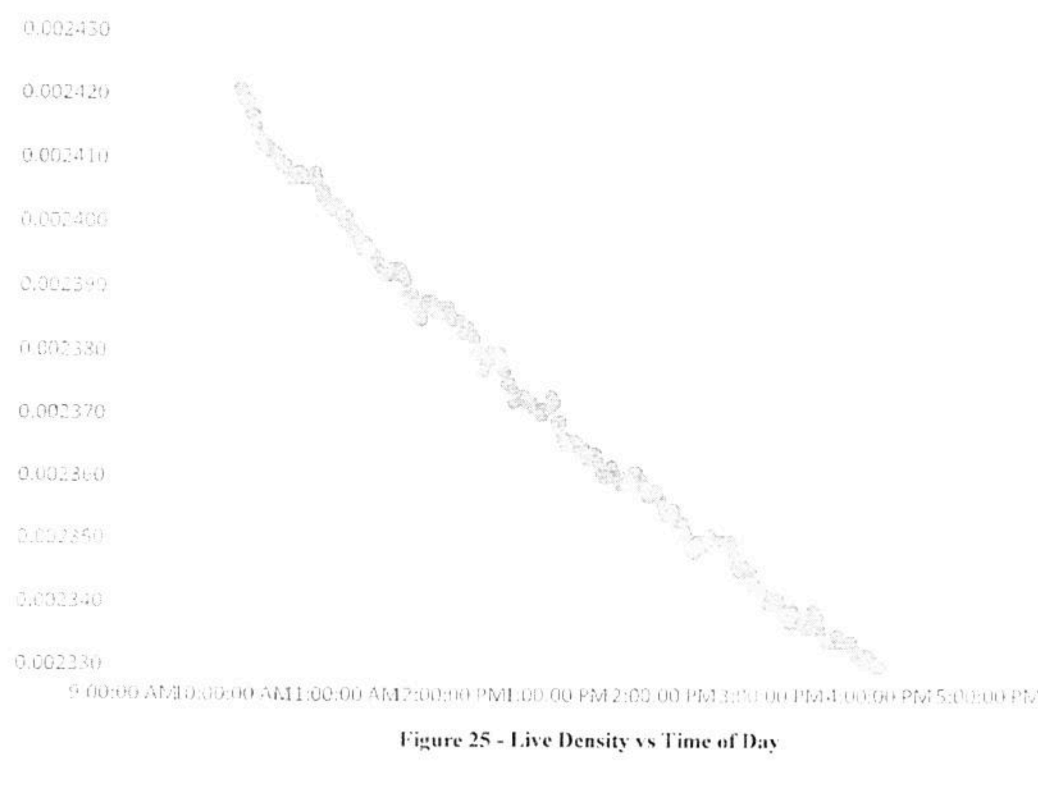


Figure 25 - Live Density vs Time of Day

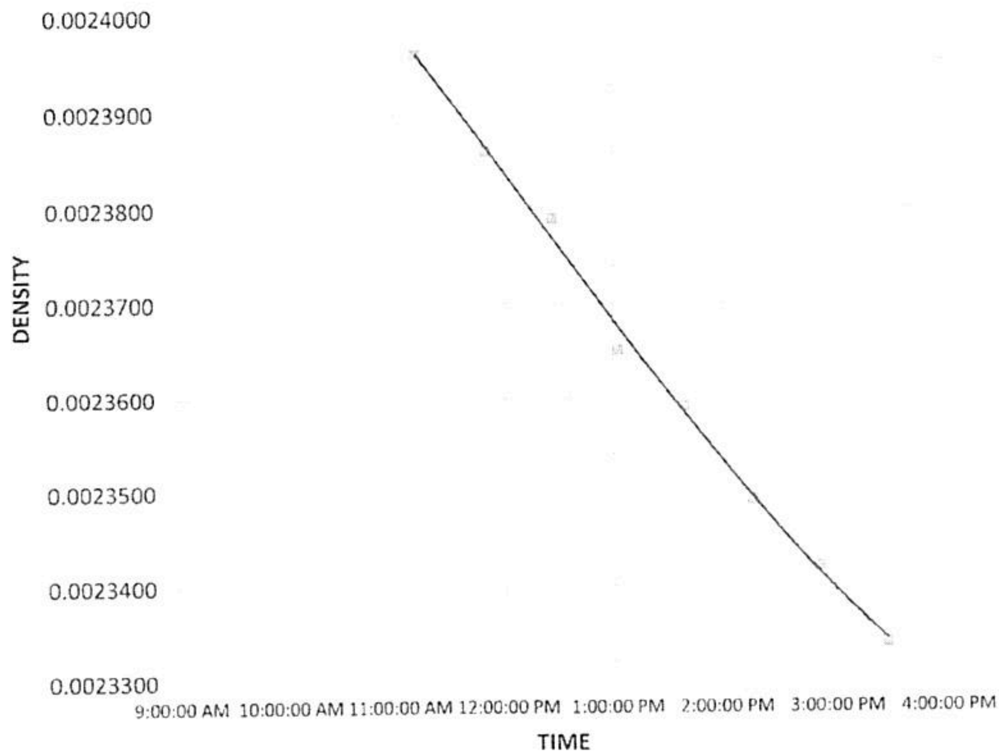


Figure 26 – Density Used vs Time of Day

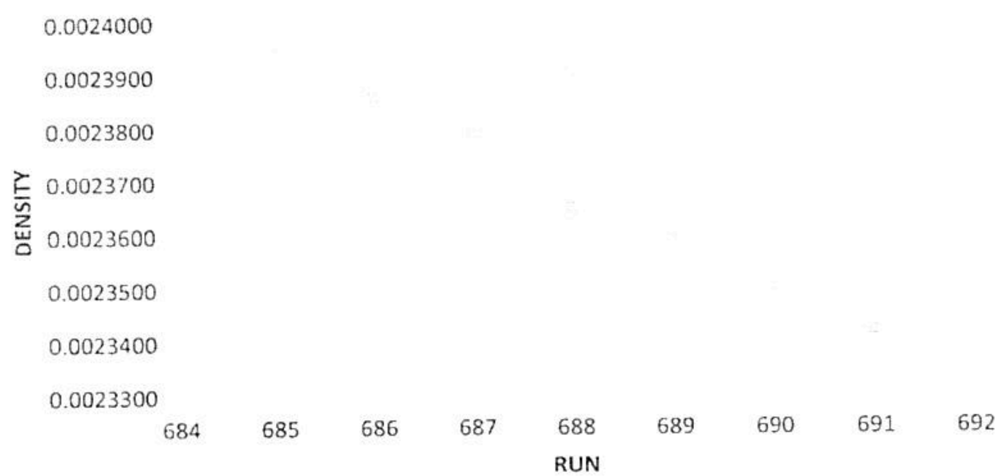


Figure 27 – Density Used vs Run Number

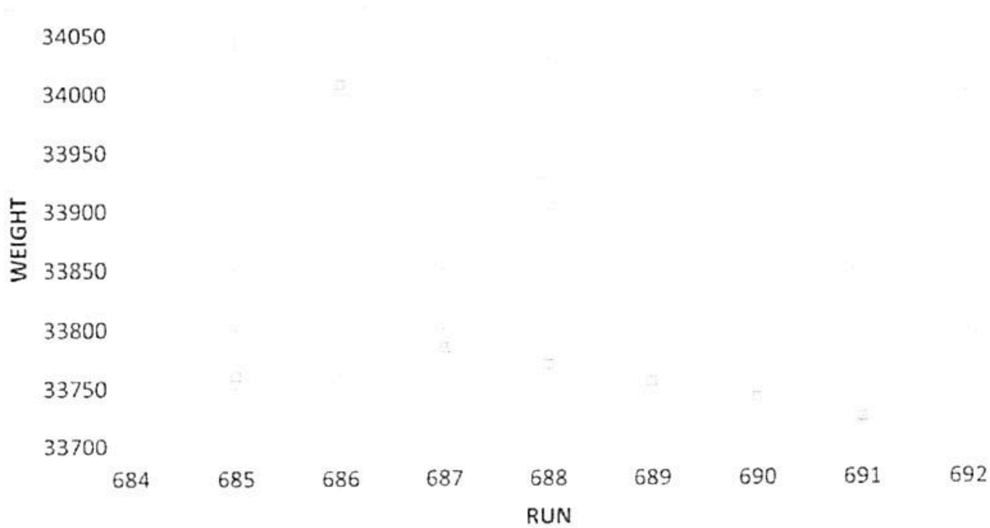
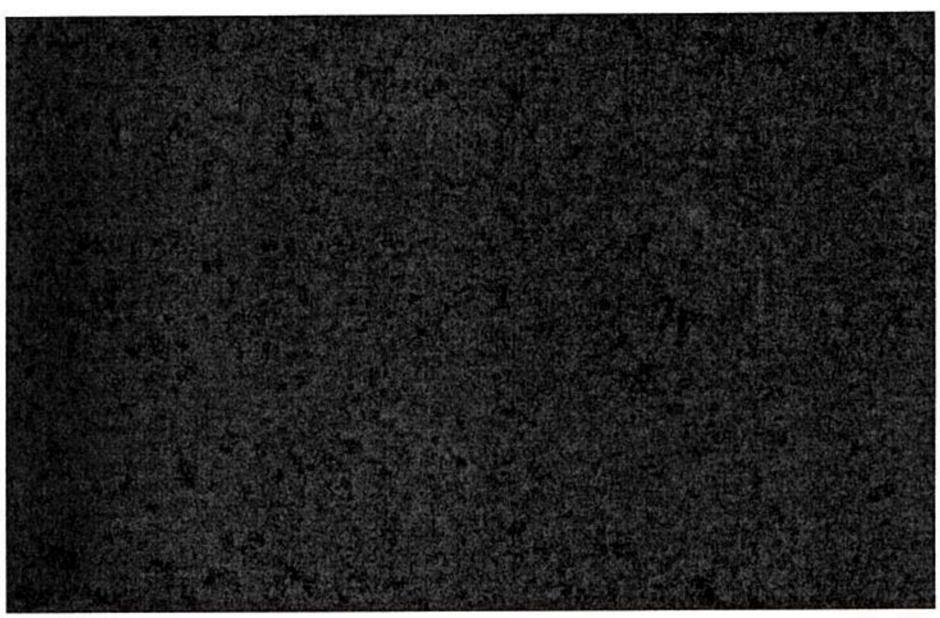


Figure 28 - Vehicle Weight vs Run Number



[redacted]

Appendix C – Computational Fluid Dynamics Data

Raw Data

[redacted]

[redacted]

[redacted]

[redacted]

Images from Computational Fluid Dynamics

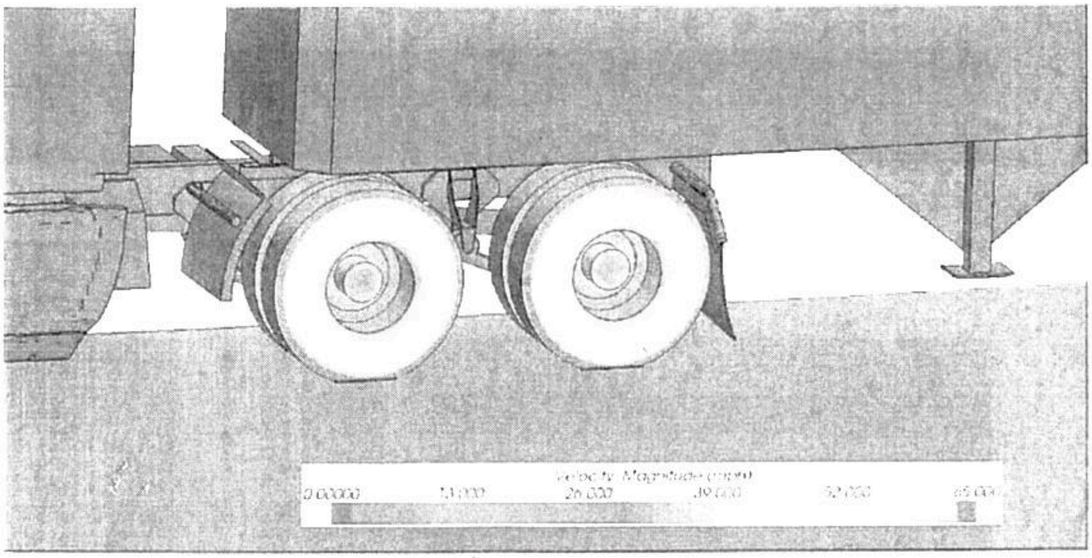


Figure 31 - Tire and Floor Velocity Boundary Conditions

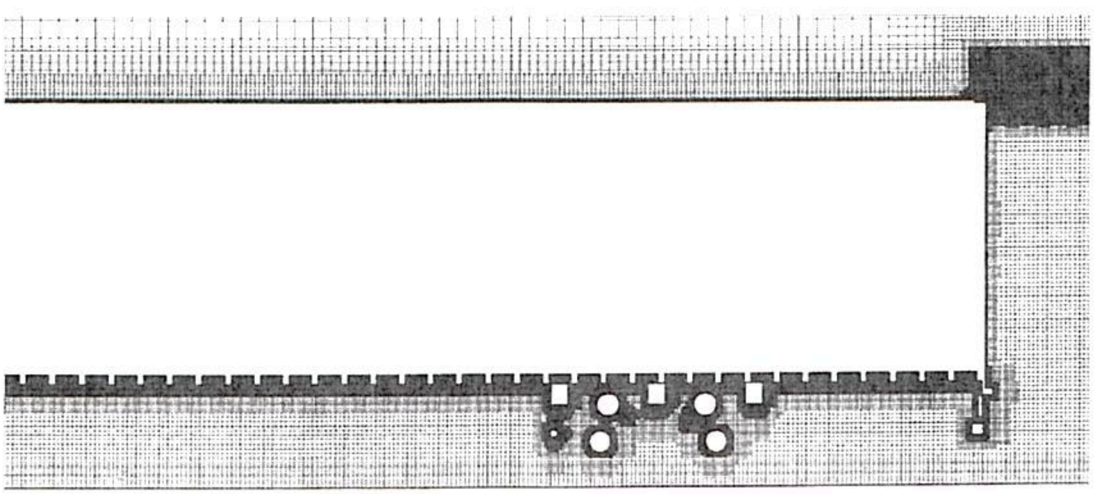


Figure 32 - Baseline Grid

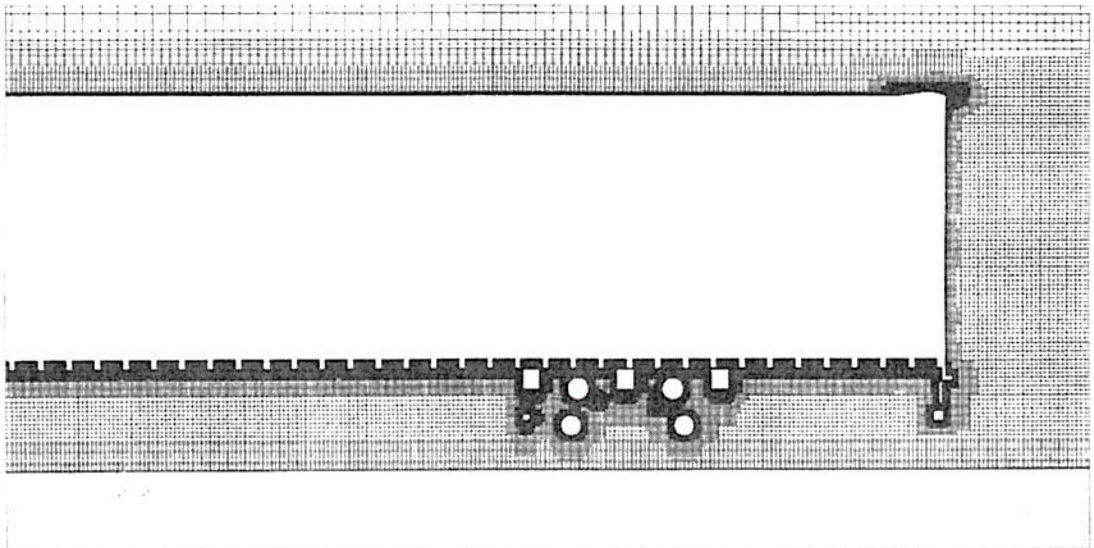


Figure 33 – TopKit Grid

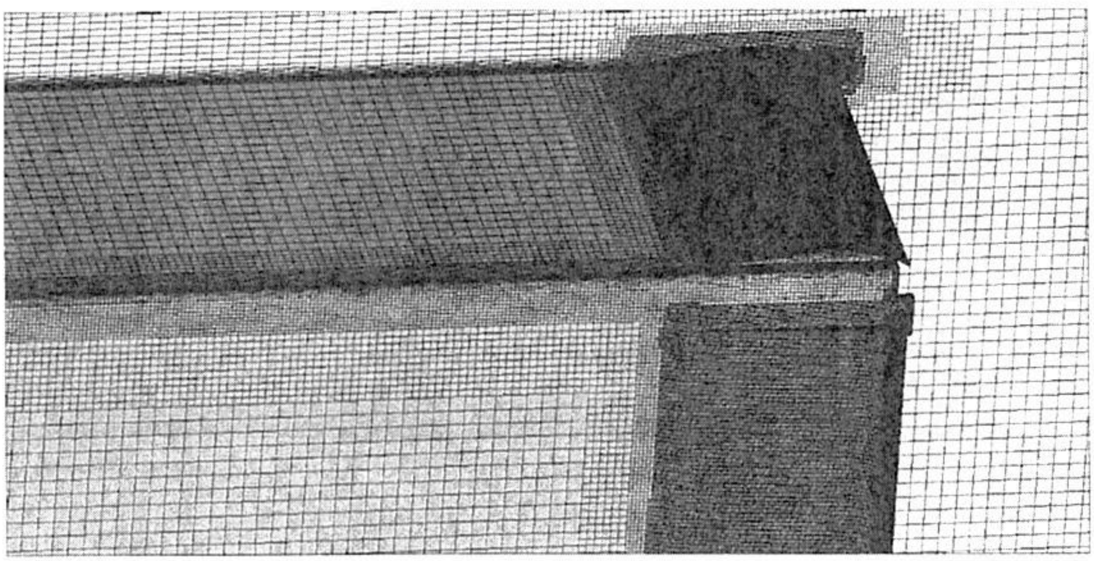


Figure 34 - TopKit Grid

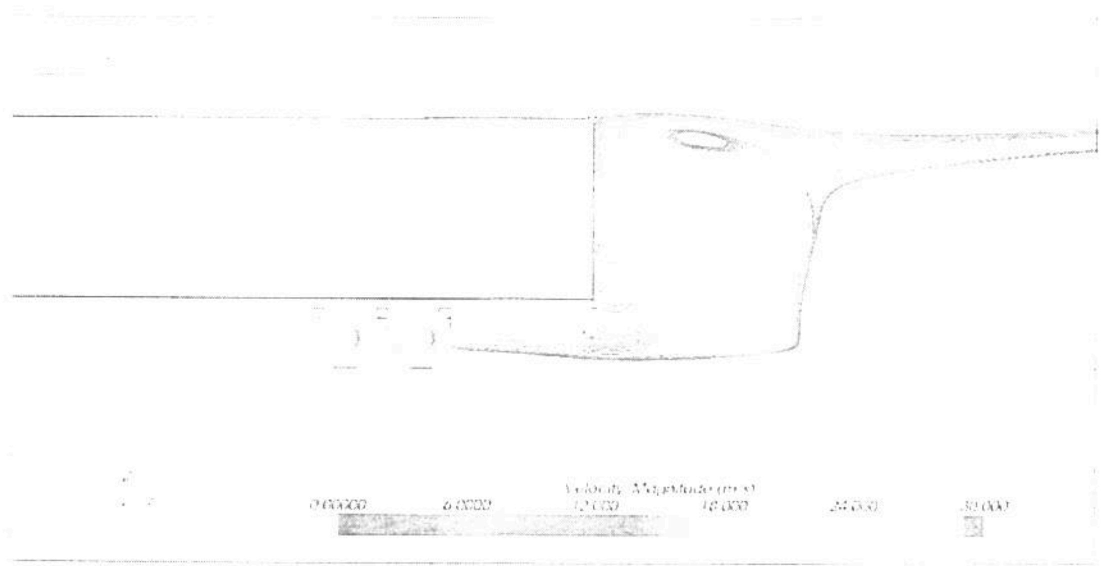


Figure 35 - Baseline Flow Visualization

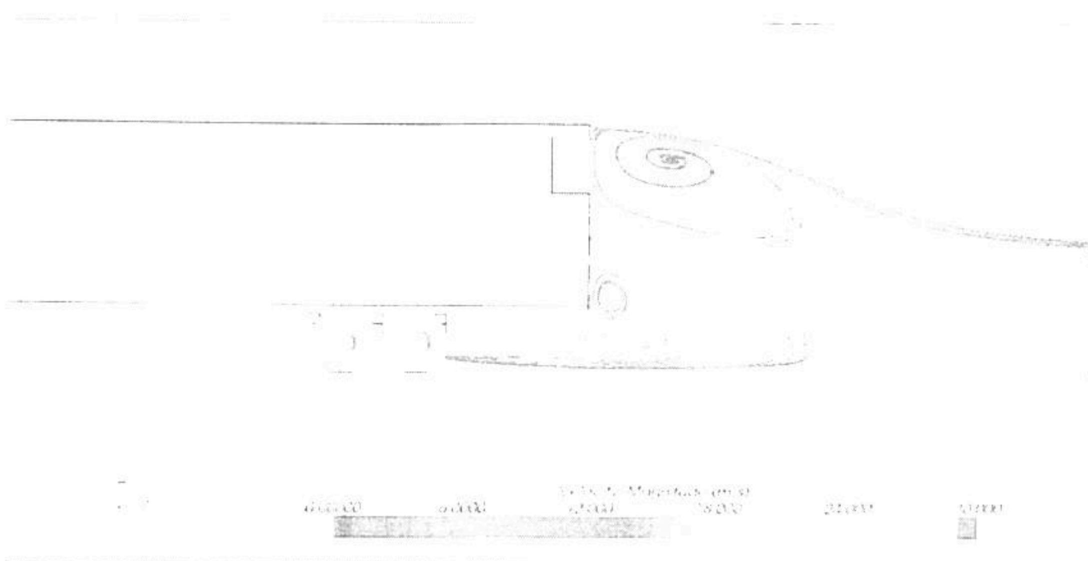


Figure 36 – TopKit Flow Visualization

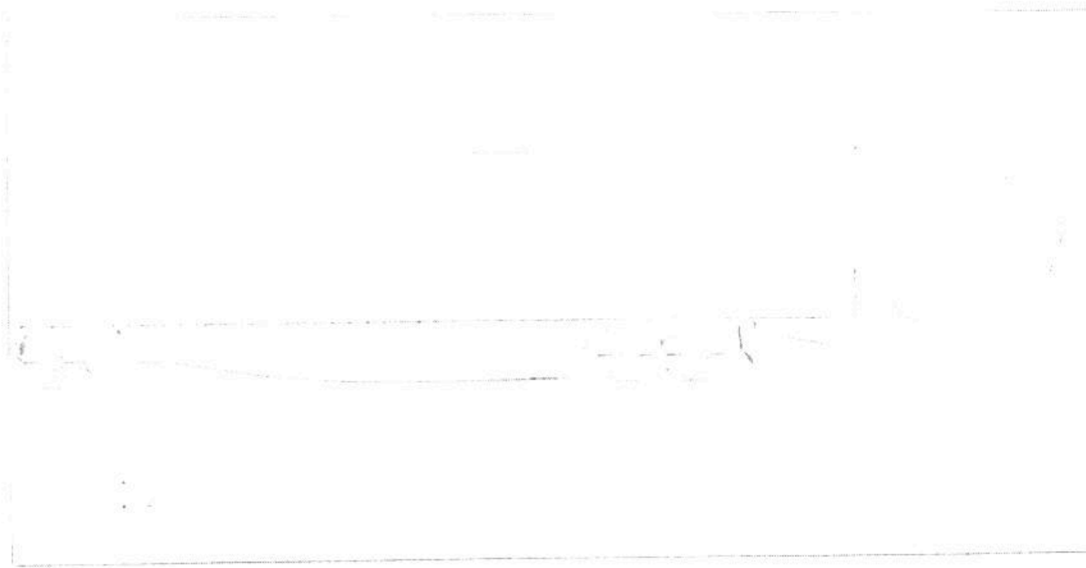


Figure 37 - Baseline Reverse Flow

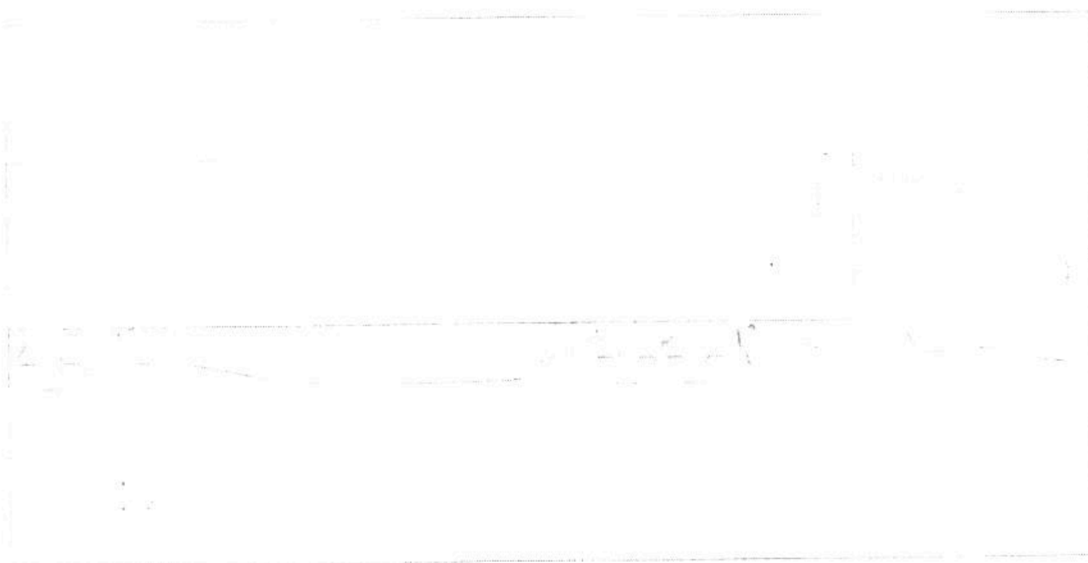


Figure 38 – TopKit Reverse Flow

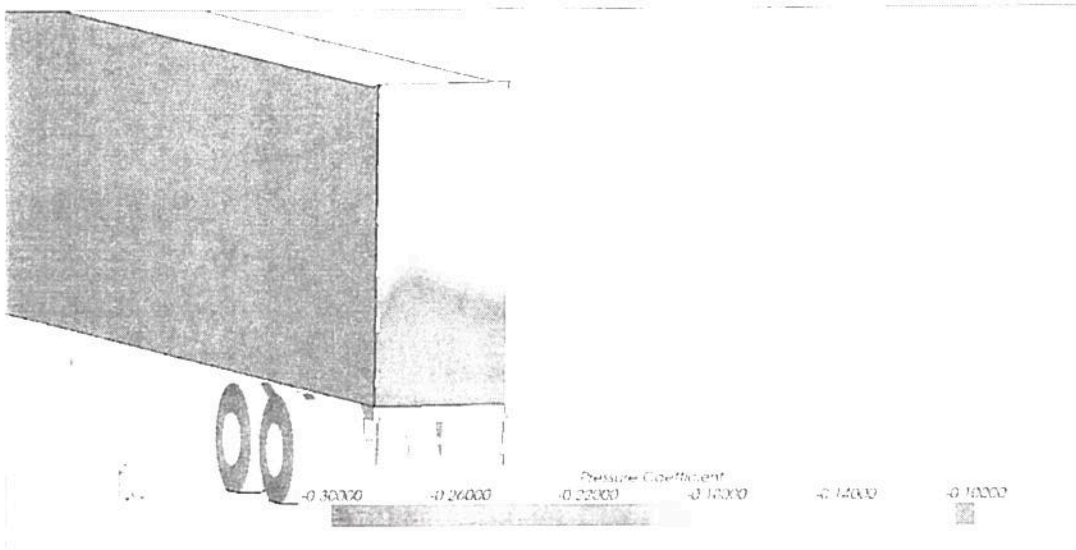


Figure 39 - Baseline Back Pressure

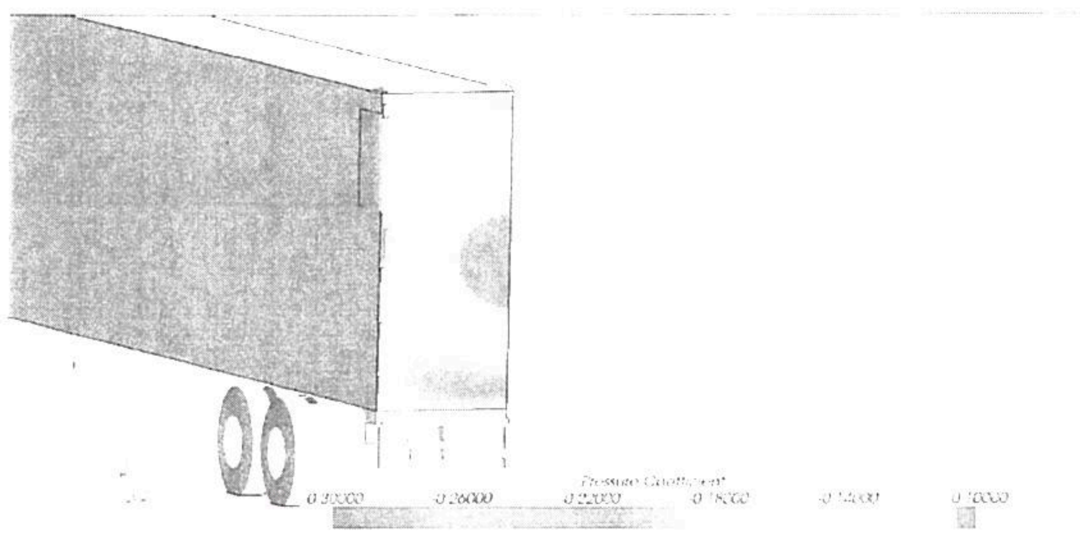


Figure 40 – TopKit Back Pressure

TRACTOR TRAILER COASTDOWN &
COMPUTATIONAL FLUID DYNAMICS COMPARISON TEST

Evaluation of SmartTruck's TopKit Trailer System

Conducted by SmartTruck Systems:

Greenville, SC 29605

May 6, 2014

Table of Contents

ST045

1 Background and Introduction

SmartTruck is pleased to submit the following application for our TopKit Trailer System to EPA's SmartWay Transport Partnership program for verification.

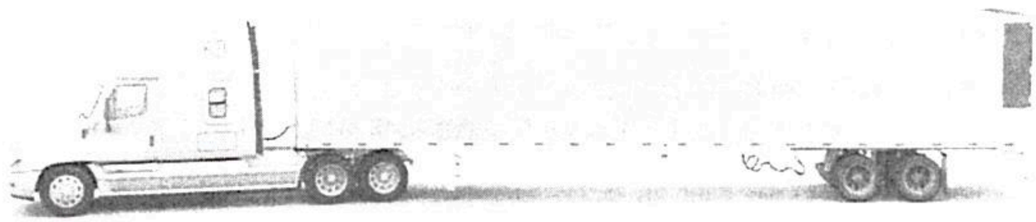


Figure 1 - SmartTruck TopKit System

The TopKit Trailer System is a *trailer aerodynamic technology* as defined by EPA's program and was designed and developed by SmartTruck Systems located in Greenville, SC. As shown in Figure 1 - SmartTruck TopKit System, the TopKit is an integrated set of components that work as a system to reduce drag. The components of the TopKit are:

A. Aerodynamic Side Fairings (2).

B. Aerodynamic Rain Guard (ARG).

Additional photos and images of the TopKit are shown in Appendix A – Photos and Images.

To develop the TopKit, SmartTruck used the same advanced aerospace engineering tools that are currently used in the highest levels of the commercial aviation and space program industries. Specifically, SmartTruck designs and initially assesses aerodynamic performance using NASA's Fully Unstructured Navier-Stokes 3D Computational Fluid Dynamics (CFD) model and solver along with CD-ADAPCO's Navier-Stokes 3D Computational Fluid Dynamics (CFD) model and solver. The computational resources needed to resolve the tremendous grid sizes and detailed air flow characteristics associated with today's Class 8 vehicles were provided to SmartTruck by NICS, The National Institute for Computer Sciences, located at Oak Ridge National Laboratory. NICS has provided SmartTruck the use of their Kraken system, a Cray XT5 supercomputer.

	Avg. CD	% CD Decrease	% MPG Increase (65 MPH)
Baseline	0.544101	N/A	N/A
TopKit	0.494754	9.07%	6.06%

Table 1 - Summary of CFD Results

As with our previous designs, once SmartTruck has completed our aerodynamic assessments with CFD, SmartTruck makes final changes and validates the performance of the TopKit by conducting state of the art coastdown testing. This process started with an evaluation [redacted] explored in CFD as well as a 72" [redacted] The 72" version was selected to maximize performance while avoiding mounting issues with exterior rub rails. SmartTruck's assessment of the TopKit Trailer System shows that installing the TopKit System on today's aerodynamic Class 8 long haul tractor trailer reduces drag by 8.76%. The fuel efficiency improvement, at steady state 65 MPH, associated with an 8.76% reduction in drag translates to approximately 5.95% improvement. [redacted]

The primary reason for this coastdown testing program is to achieve EPA SmartWay Transport Program verification for the TopKit Trailer System. However, SmartTruck has gone above and beyond the standard testing protocol by outfitting our testing vehicle with a state of the art data acquisition system. This system has almost 800 potential channels to monitor and record a wide variety of vehicle systems and effects, including true air speed, wheel speed, gps speed, wind direction, steering input and any/all data gathered through the vehicle's engine bus.

Coastdown testing on the TopKit System was conducted April 17th, 2014 at Michelin's Laurens Proving Grounds in Laurens, South Carolina. Test results using the Test Run to Baseline Run comparison conclude the TopKit Trailer System produces a 5.95% improvement in fuel efficiency at 65 MPH.

2 Coastdown Testing

2.1 *Approach*

SmartTruck Systems' testing program was done in accordance with proven coastdown testing techniques. To further facilitate proper scientific protocol, a consistent 2011 Wabash 53 foot dry van trailer, provided by XTRA Lease Trailer Rentals, and Navistar 2010 model year ProStar Tractor was used. This combination remained consistent throughout testing.

The test truck was equipped with state of the art data acquisition systems. These systems have almost 800 potential channels to monitor and record a wide variety of vehicle systems and effects, including, but not limited to:

- True air speed via pitot static tube
- [redacted]
- GPS speed
- Engine rpm
- Yaw angle/wind direction
- Steering input
- Engine fan RPM

Weather was monitored by a Davis Vantage Vue weather station, located next to the track, to provide data as close to what the truck was exposed to as possible.

2.2 *Test Protocol*

2.2.1 Discussion of Coastdown Testing For Heavy Vehicles

EPA's Modified Protocol based on SAE J2263 coastdown protocol has been suggested for testing of Class 8 trucks to qualify aerodynamic devices on the tractor and the trailer. Our experience has been, after testing more than 200 different aerodynamic configurations and over 700 individual test runs, is that there are several issues with the suggested protocol which make it virtually impossible to achieve accurate results and very difficult and expensive to perform the testing.

2.2.2 SAE J2263 Protocol Issues in Heavy Truck Testing

2.2.2.1 Issue 1 – 70 mph to 17 mph Coastdown Interval

This coastdown interval is required for the data reduction technique spelled out in the protocol to work accurately (i.e. obtaining the zero velocity drag force for rolling resistance correction). The J2263 protocol was developed for light vehicles (basically automobiles and light trucks) that could accelerate to 70 mph and then coastdown to less than 17 mph in a reasonable distance (about 6,000 feet) due to high drag to weight ratio typical of cars and light trucks. There are many facilities that are available that are long enough for this test with cars and light trucks. However, a Class 8 tractor-trailer combination, completely unloaded, weighs in the order of 36,000 pounds. It's power to weight and drag to weight is a fraction of a car or light truck. Consequently the total distance required to perform the SAE J2263 coastdown is typically 13,000+ feet. See Figure 2 - Calibrated Truck Model Result.

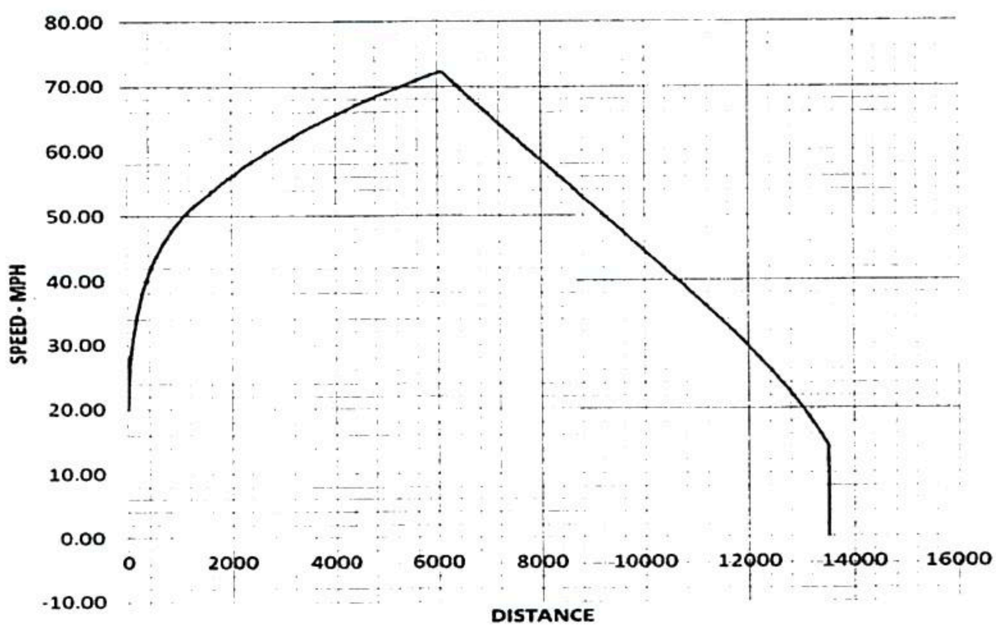


Figure 2 - Calibrated Truck Model Result

Not many facilities offer this size track. SmartTruck has a Space Act agreement with NASA to use their Space Shuttle runway (which is 18,000 feet in length) and we have tested there using a coastdown of 70 mph to less than 15 mph on several occasions. The Shuttle runway is active and has heightened security so scheduling and operations are quite difficult. Our experience is that this is a very expensive facility that few would take advantage of, yet the J2263 protocol, as currently written, will require this type of venue.

2.2.2.2 Issue 2 – Assumption That the Rolling Resistance and Friction Is Constant i.e. Does Not Vary With Speed

Rolling resistance (and friction) is accounted for in the SAE J2263 protocol by plotting the instantaneous total force calculated from the measured dV/dT and vehicle weight versus velocity and then extrapolating it to zero speed. Since the aerodynamic drag is zero at zero speed, the intersection represents the rolling resistance and friction forces at zero speed. This force is then subtracted from the total force to extract aerodynamic drag at the desired speed. Figure 3 below is a typical curve of this sort from one of SmartTruck's tests at the Kennedy Space Center.

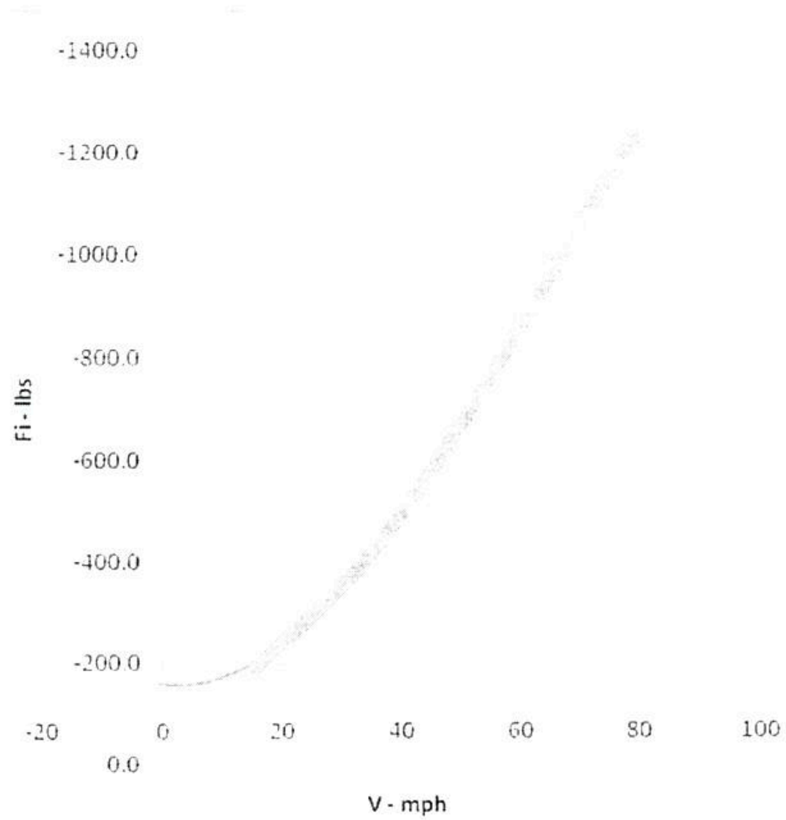


Figure 3

As can be seen the intercept with the y axis is at a retarding force of 159 pounds. This divided by the weight gives a coefficient of rolling resistance (Crr) of 0.0044. This is consistent with our experience with the tires used on our test trailer at zero speed. However, if one uses data on Crr from the tire companies and literature one finds out that Crr varies as the square of speed. Indeed our data for the tires we use and other data on other test tires suggest that the coefficient of rolling resistance follows the following formula:

$$Crr = Crr_o + (5x10^{-7}) * V^2$$

When this formula is used for data reduction a much more accurate drag prediction results because, in fact, the rolling resistance and friction drag are not constant and the difference in rolling resistance at speed and the zero speed value gets added to the "aerodynamic" drag value. Figure 4 below is again from our Kennedy testing and shows the difference in the drag prediction when Crr is constant and when the formula above is used.

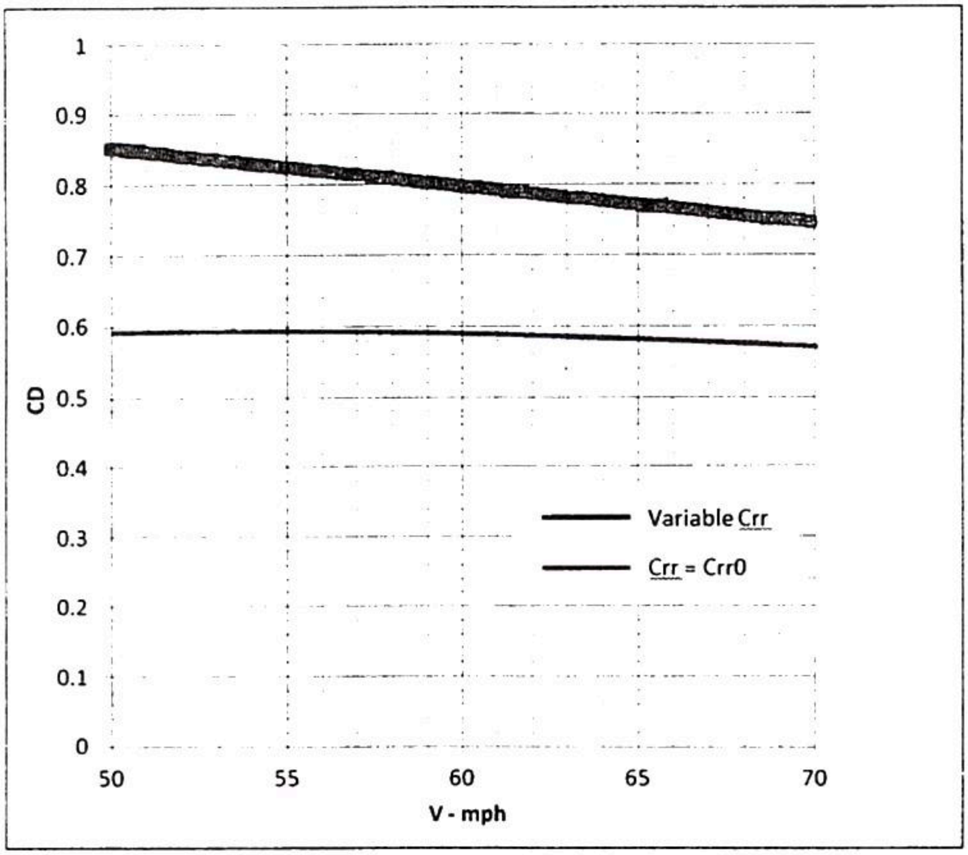


Figure 4

The red line is the Cd predicted using the variable Crr while the blue line is the Cd predicted using the constant value of Crr=Crr_o.

The red line is nearly constant with speed and very closely agrees with the CFD predicted value of Cd as well as the Cd implied by our fuel mileage testing of this configuration. The Cd predicted by the SAE J2263 protocol is high, due to the infusion of rolling resistance and friction drag in the aerodynamic drag levels, and significantly variant with speed which is inconsistent with any other analysis of drag. Errors in the relative drag levels using the SAE J2263 are of course smaller than the absolute level error but still can be significant since the Crr error is constant. As the aerodynamic drag is reduced the Crr error is a larger percent of the total predicted drag level thus increasing the Cd level relative to a higher drag baseline. Using a varying Crr is not perfect but errors in the Crr slope represent much smaller differential errors than just assuming the slope is zero.

Again, light vehicles get away with this because of their higher aero drag to rolling resistance ratio due to their lighter weight. In heavy vehicles the error is too great.

2.2.3 The SmartTruck Heavy Vehicle Coastdown Test Protocol

Simply stated, the SmartTruck protocol uses a combination of high speed test runs with coastdown from 65 mph to 40 mph and low speed test runs coasting from 25 mph to 0 mph to obtain the required high speed drag data and the value Crr_0 with which to correct the total drag. Figure 5 – Simulated Coastdown Distance below shows that the accelerate-coastdown distance for the high speed coastdown is just over 6,000 feet and the coastdown portion required is just under 4,000 feet for a vehicle weight of 36,500 lbs.

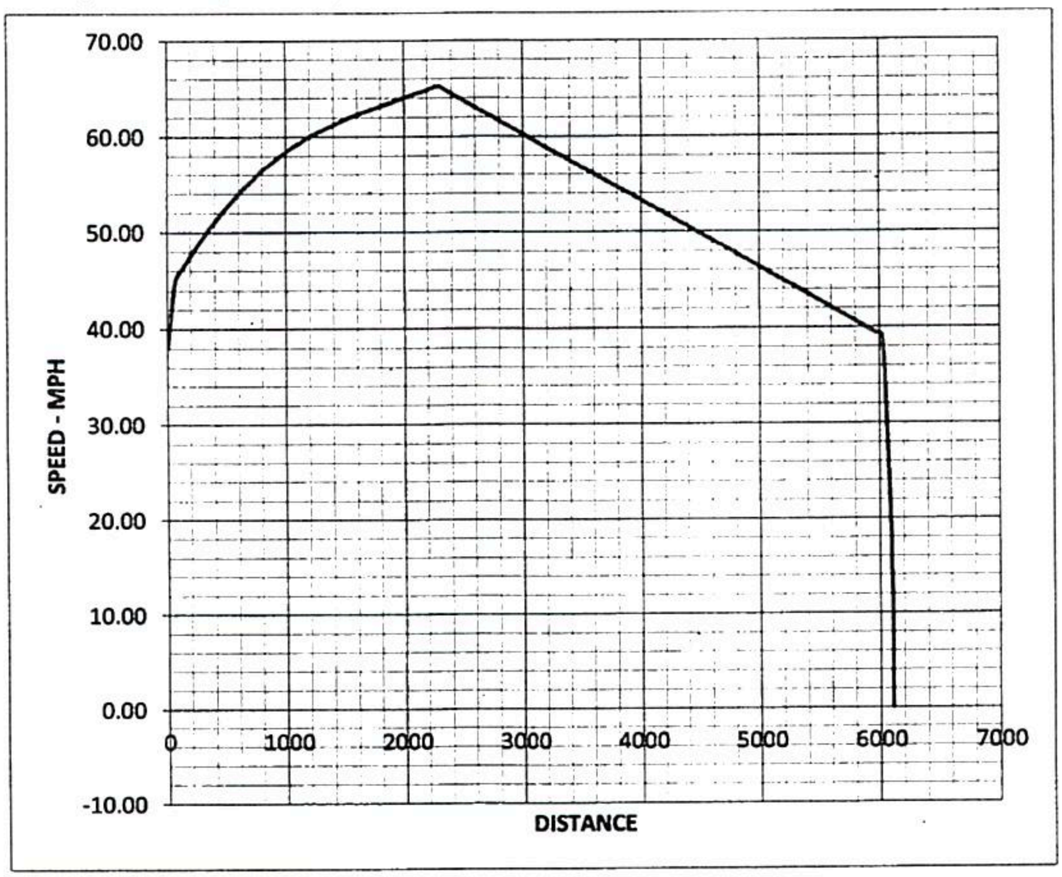


Figure 5 – Simulated Coastdown Distance

There are many facilities available with this length and adequate turn around tracks. SmartTruck has tested at Michelin's Laurens Proving Grounds Track 9 (available for rent to the public) and an inactive runway at the South Carolina Technical Aviation Center (SCTAC) in Greenville to perform these tests. This allows local, cost effective testing to be done on many configurations. Figure 6 - Low Speed Lap, Figure 7 - High Speed Laps and Figure 8 - High Speed Laps below shows actual raw data from the SmartTruck data system for a single configuration run.

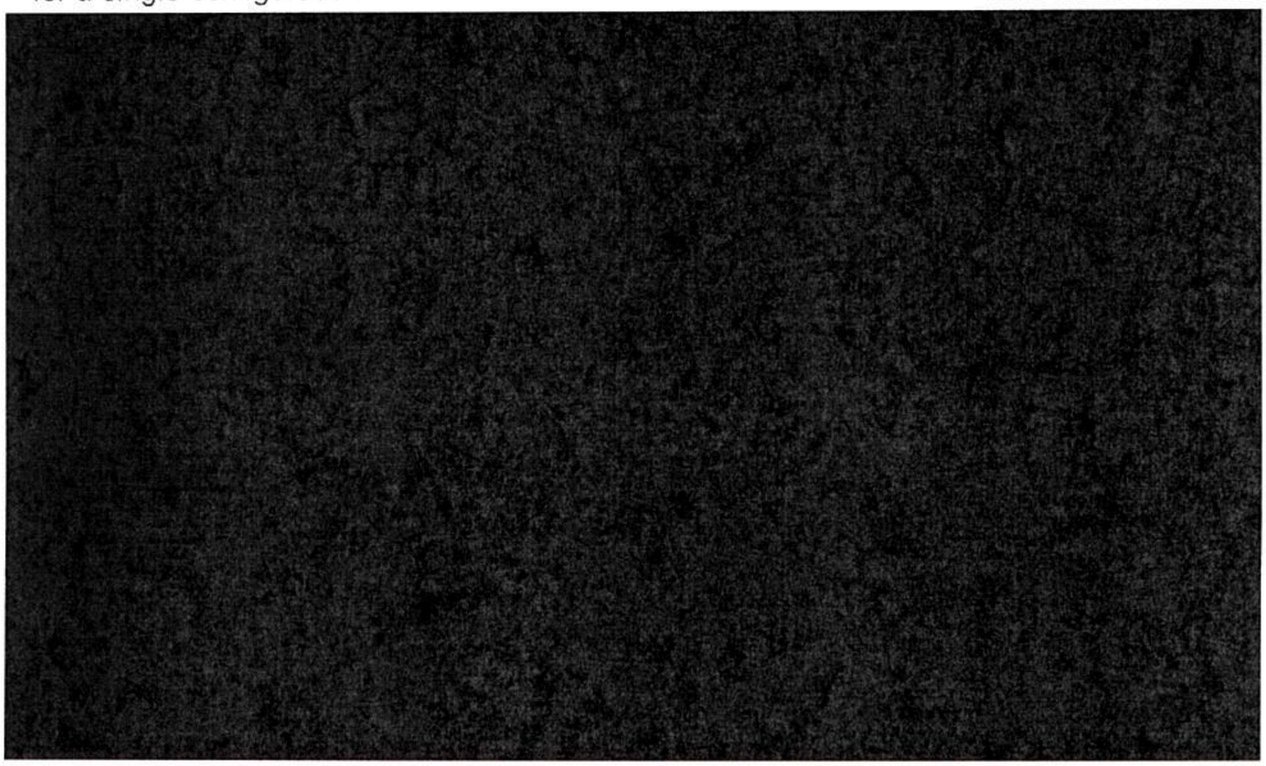


Figure 6 - Low Speed Lap

Figure 7 - High Speed Laps

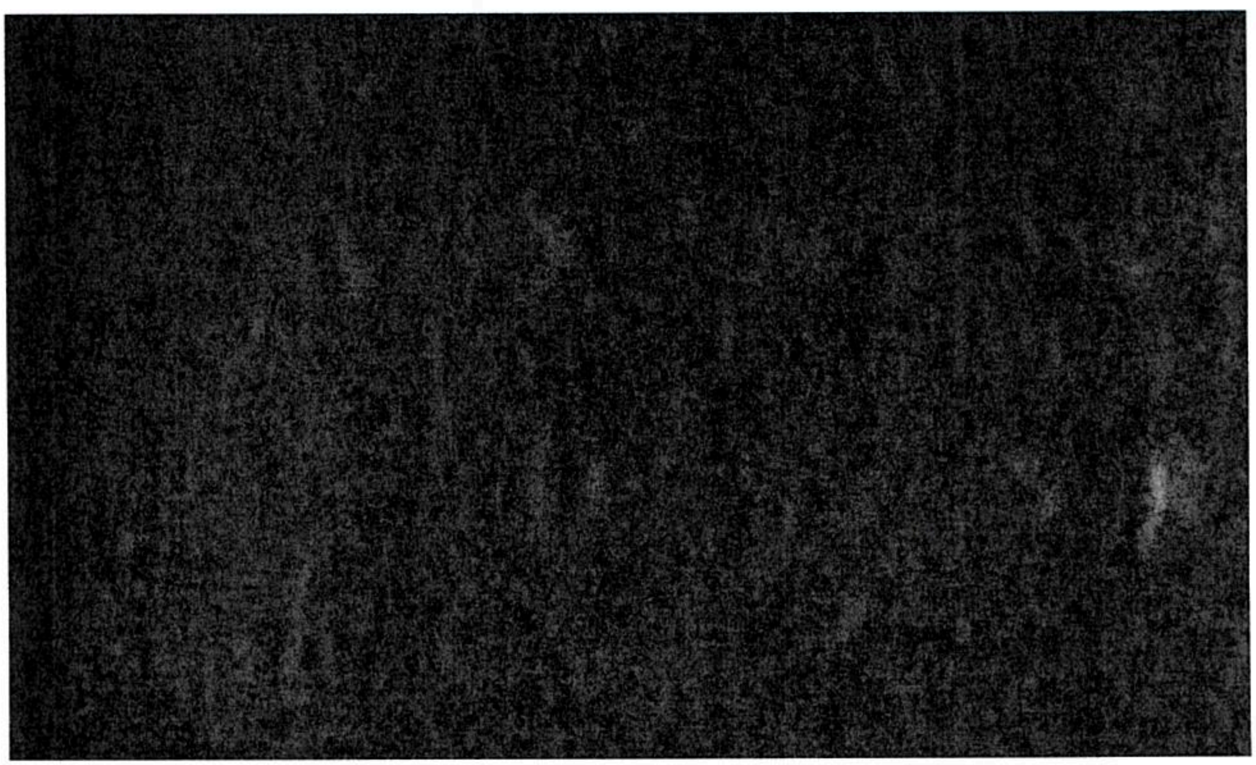


Figure 8 - High Speed Laps

The first lines are the truck airspeed data from a calibrated pitot static system on board the tractor. The second lines are from a highly accurate GPS sensor and the third lines are the vehicle speed measured with [redacted] While the airspeed system is not strictly needed for good Cd measurement as long as the winds are low and consistent, it is needed to measure the time variant Cd during any given run. SmartTruck uses the time variant Cd to get average Cd, and to see if our aerodynamic modifications reduces or increases the frequency or magnitude of Cd variations. We also use the airspeed system data to disqualify a run with excessive gusting or yaw within in a run. We measure the yaw angle with our data system directly but again this is not strictly necessary for good average Cd data if a good weather station is used as is required by both protocols. Airspeed data contains a significant high frequency content that is related to cab vibration not gusting. This must be removed from the data to obtain good time variant Cd information. The chart below, Figure 9, shows the raw signal, blue, and the filtered signal, red, that is ultimately used in the calculations.

[redacted]

Figure 9

Figure 10 - Low Speed Run Results show results of the analysis of the low speed runs used to obtain Crr for removal of the rolling resistance and friction from the total retarding force to get the aerodynamic drag force.

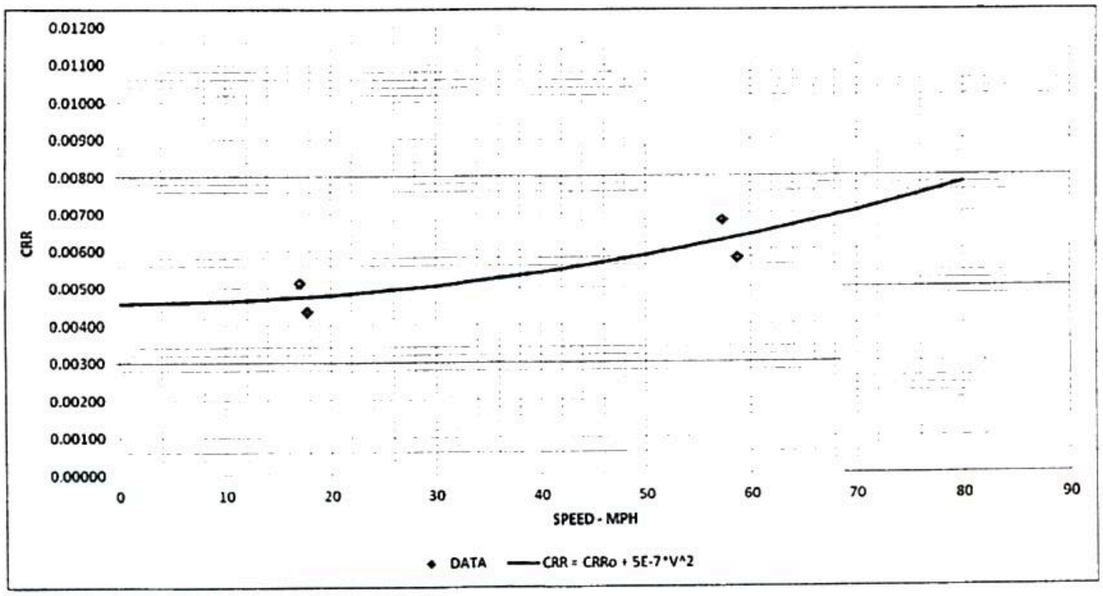


Figure 10 - Low Speed Run Results

Figure 11 – CD vs Time Baseline and TopKit Compared shows Cd vs. time data for both Baseline and TopKit on one of our Track 9 test runs.

[redacted]

Figure 11 – CD vs Time Baseline and TopKit Compared

The blue line is the time accurate Cd, while the orange line is the average Cd.

To obtain a final Cd value, SmartTruck averages all Cds from each individual run for the configuration. Average Cds are also checked for too great a run to run variance in which case that run is eliminated and repeated.

SmartTruck has tested over 200 configurations on over 700 runs using this protocol. We test our baseline configuration at every test and several times during a test day and consistently get accurate and repeatable results both within a test day and between tests going back over two years.

2.3 Test Procedure

[redacted]

After the test run is completed, [redacted] while [redacted] This method allows for more accurate correction of high speed aerodynamic signals from low speed rolling resistance.

[redacted] By doing this, [redacted] As a secondary data check, [redacted]

After each run a pit stop is preformed, where engineers will:

- Download SoMat data acquisition system data.
- Review of coastdown data to ensure integrity.
- Check steer tire pressures.
- A tractor check list is performed to ensure it was still in proper working condition.
- All aerodynamic parts are checked to ensure proper working functionality.
- Weather station data is downloaded and checked to ensure good weather conditions.

2.4 Vehicle Preparation

- All vehicle axles were aligned to manufacturer's specifications. Tractor and trailer axle bearing and brake adjustments were made at this time.
- The tractor trailer gap was set in a commonly used long haul configuration. Specifically, the King Pin location was set so that the back of the cab to the front of the trailer gap was [redacted]
- The rear trailer slider was set to the California standard of 40 feet.
- The main fuel tanks were [redacted]
- Documentation of the test vehicle configuration and proper installation of the TopKit components were completed prior to each test.
- The same fuel from the same source was used throughout the entire test procedure. And a [redacted] was used ensure an accurate [redacted]

2.5 *Pre-test Inspection*

Each test day before vehicle warm-up, the vehicles were run for brief periods and checked to ensure they were in good working order. The tire pressures were checked to ensure proper inflation. [redacted] was used ensure an [redacted]

2.6 *Warm-up*

Prior to each testing day the truck is operated on the track for a one hour warm-up [redacted]

2.7 *Aerodynamic Kit Changes*

Kit changes are a periodic part of coastdown testing. SmartTruck Systems [redacted] For the most consistent scientific results, this procedure is followed regardless if there is an aerodynamic kit change or not. However, if an aerodynamic kit change [redacted] a warm-up must be performed again.

2.8 *Vehicle Weight*

Fuel consumption for each vehicle was measured for each run completed. Consumption, measured in pounds, was determined by reading the total fuel used from the engine data and calculating the difference from the previous run. Weight for each kit configuration was also accounted for.

2.9 *Vehicle and Equipment Specifications*

	Tractor	Trailer
Unit #	USDOT 497152	U94355
Make	Navistar	Wabash

Model	Pro Star	N/A
V.I.N.	3HSDJSJR7BN409752	1JJV532D5CL726150
Engine	Nvistar Maxforce	N/A
Odometer	284,779	N/A
Tires-Steer	Michelin X Green 275/80R22.5	N/A
Tires-Drive/Trailer	Michelin X Line Energy D 275/80R22.5	Michelin X Line Energy 275/80R22.5
Manufacture Year	2010	2011

Table 2 – Tractor, Trailer Information

Purpose	Sensor	Type	Capacity
DAQ	SoMat eDAQlite	Rugged Data Recorder	Analog, Strain Gage, Thermocouple, Digital I/O, Pulse Counter, GPS, Vehicle Bus
Steering	Celesco SG1-80-3	Potentiometer	Essentially Infinite Resolution
Fan RPM	Monarch Remote Optical Sensor	Optical Sensor	1-250,000 RPM
Pitot	Senserion SDP2000L	Low Range Differential Pressure Transducer	0.0-0.5 PSI, Temperature Compensated
Windvane	World Encoders SR12-512A/12-30	Absolute Shaft Encoder	512 (9bit) Resolution
5th Wheel	ACCU-Coder 25T-425G-1200NV1QOC-9D	Video Encoder	1200 Counts Per Revolution
GPS	Garmin GPS18x-5Hz	GPS Sensor	5Hz Measurement Pulse Output, 0.2 second increments of UTC time

Table 3 - Instrumentation Information

2.10 Description of Test Facility

Testing was conducted in Laurens, South Carolina at Michelin's Laurens Proving Grounds (LPG). LPG is a state of the art testing facility with a total of nine unique tracks including: a main test track, road course, wet handling, gravel endurance, off road inclines, heavy truck loop, noise, vehicle dynamics and drift/pull.

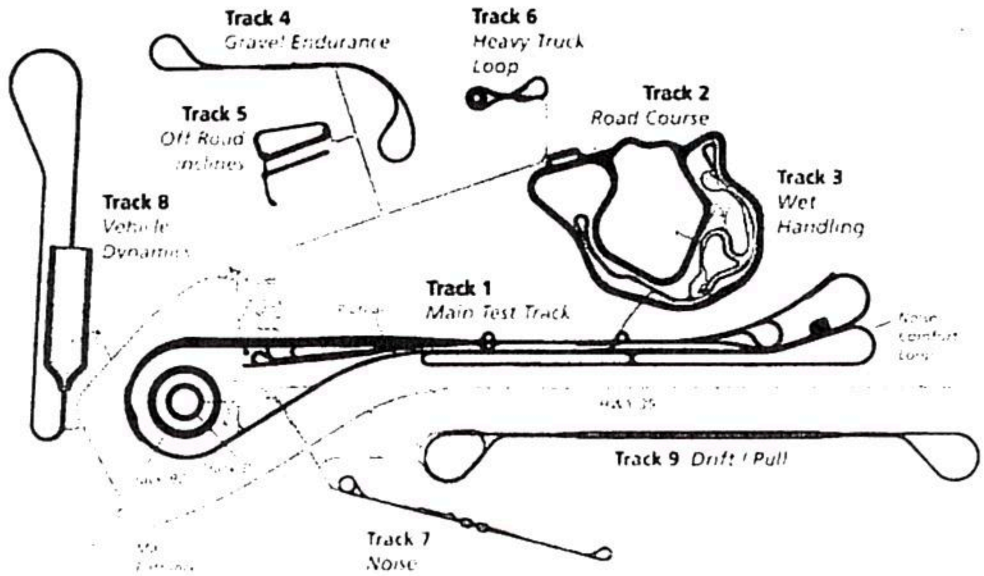


Figure 12- LPG Facility Map

SmartTruck currently takes advantage of LPG's Track 9, Drift/Pull. This track is a 4,800 foot straightaway with turnaround loops on either end for a total length of 1.25 miles. The track width is 40 feet in the turnarounds and 80 feet in the straightaway. The surface of the track is asphalt with a surface texture (Macro/Micro) of smooth/rough. Track 9 also has a near perfect flatness over the straightaway length with an International Roughness Index (IRI) of 37.4 in/mile.

Figure 13 - Track 9, Drift/Pull

2.11 Calculation Equations

2.11.1 Rolling Resistance

Rolling resistance at zero speed was measured for each configuration from the low speed runs and the actual RR curve was:

$$Crr = Crr_o + (5x10^{-7}) * V^2$$

Where:

Crr is the coefficient of rolling resistance
Crr_0 is the coefficient of rolling resistance at zero speed
V is the measured vehicle speed in ft/sec

This was done for each configuration.

2.11.2 Drag Calculation Equations

$$D_{aero} = \left(\frac{W_c}{g}\right) * \left(\frac{dV_{wheelspeed}}{dT}\right) - Crr * W$$

$$Cd = \frac{D_{aero}}{A_{ref}/\left(0.5 * \rho * V_{airspeed}^2\right)}$$

Where:

W_c is vehicle weight in lbs. (which includes the inertial effects of the wheels)
g is the gravitational constant, 32.2 ft/ sec^2
W is vehicle weight in lbs.
A_{ref} is the reference area of the vehicle, 97.2 ft^2
ρ is measured air density in (slug • ft)/sec^2
$V_{airspeed}$ is the measured airspeed in ft/sec
$V_{wheelspeed}$ is the measured vehicle speed in ft/sec
Crr is the coefficient of rolling resistance

2.12 Test Configuration

Following the conclusion of all baseline testing and calculations, the test truck was outfitted with the TopKit Trailer System. This configuration consists of:

A. Aerodynamic Side Fairings (2).
B. Aerodynamic Rain Guard (ARG).

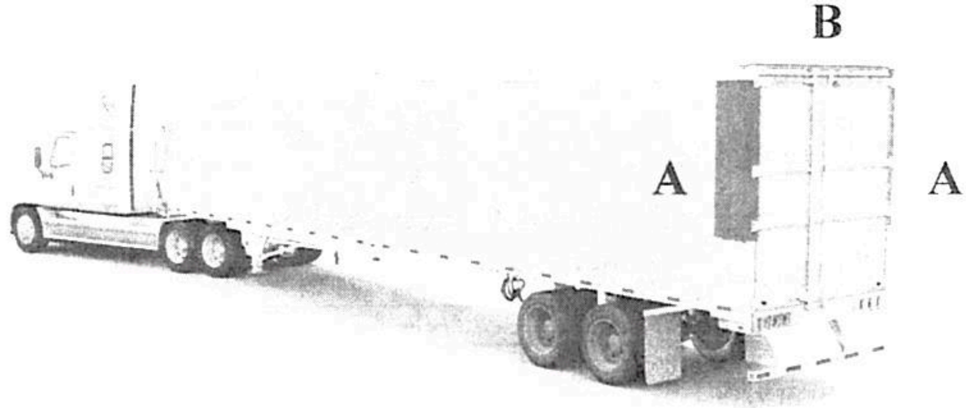


Figure 14 - Rear View of Aerodynamic Side Fairings and Aerodynamic Rain Gutter

3 Computational Fluid Dynamics (CFD)

3.1 CFD Approach

SmartTruck first validated the TopKit [redacted] needed to achieve MPG improvement greater than 5%. Because CFD predicted greater than 5% with [redacted]

3.2 Computer Systems and Software

CD-Adapco's Star-CCM+ v8.02 software was used for gridding and computations. Post Processing was performed by both Tecplot360 as well as Star-CCM+.

All grids were pre and post processed on an internal machine outfitted with a 3.20GHz Intel i7 Processor with 12 cores and 64GB of RAM.

All computational runs were performed on The National Institute for Computational Sciences (NICS) super computer Kraken XT5. Kraken is composed of 112,896 compute cores (two 2.6GHz six-core AMD Opteron processors per node) and 147TB of compute memory (16GB of memory per node). Kraken has a peak performance of 1.17 PetaFLOP.

More information about NICS and the Kraken supercomputer can be found at: http://www.nics.tennessee.edu/computing-resources/kraken.

3.3 Testing Method

All runs consisted of a half model, steady state analysis utilizing SmartTruck Systems (STS) gridding version 9. Rotating vehicle tires and a moving floor were also used.

Grid Type	[redacted]
Flow Solver	Navier Stokes, [redacted]
Number of Prism Layers, Critical Flow Areas	[redacted]
Boundary Layer First Cell Size (mm)	[redacted]
Total Number of Cells:	
Baseline	[redacted]
3 PIECE TopKit	[redacted]
Far Field Boundaries:	
For/Aft (m)	[redacted]
Side/Side (m)	[redacted]
Above/Below (m)	[redacted]
Boundary Conditions:	
Tires	Rotating Tire to Match Vehicle Speed
Ground	Moving Viscous Floor to Match Vehicle Speed
Free-Stream	Fully Viscous Solution
Wall Treatment	[redacted]
Air Speed (m/s)	29.0576
Density (kg/m^3)	[redacted]
Reference Pressure (Pa)	[redacted]
Frontal Area (m^2)	[redacted]
Turbulence Model	[redacted]
Turbulent Viscosity Ratio	[redacted]

Table 4 - CFD Parameters

3.4 Test Configuration

SmartTruck System's TopKit Trailer System consists of:

A. Aerodynamic Side Fairings (2).

B. Aerodynamic Rain Guard (ARG).

4 Test Data

4.1 Coastdown Testing

4.1.1 Baseline Segment

Aero Kit	Run	Crr_0	CD	Avg. Temp	Avg. Wind	Air Density	Vehicle Weight	Avg. Steer Tire Pressure	Time
				deg. F	MPH	slug/ft^3	lbs.	PSI	Eastern
[redacted]									

Table 5 - Baseline Test Data

Table 5 - Baseline Test Data shows the test data from the baseline segments. [redacted] Therefore the average Drag Coefficient number of 0.61477 was found to be accurate and used in comparison to the TopKit.

	Avg. CD	% CD Decrease	% MPG Increase
Baseline	0.61477	N/A	N/A

Table 6 – Baseline Performance Summary

4.1.2 Test Segment

Aero Kit	Run	Crr_0	CD	Avg. Temp	Avg. Wind	Air Density	Vehicle Weight	Avg. Steer Tire Pressure	Time
				deg. F	MPH	slug/ft^3	lbs.	PSI	Eastern
[redacted]									

[redacted]

Table 7 – Aerodynamic TopKit Test Data

Table 7 – Aerodynamic TopKit Test Data shows the test data from the TopKit segments. Compared to the Baseline coastdown test, the average percent drag coefficient change was 8.76% which equates to 5.95% improvement in MPG at 65 MPH. The TopKit's average Drag Coefficient number was found to be 0.56089.

	Avg. CD	% CD Decrease	% MPG Increase (65 MPH)
TopKit	0.56089	8.76%	5.95%

Table 8 - TopKit Performance Summary

[redacted]

To ensure accurate results, SmartTruck Systems has used [redacted] to evaluate and certify its data. The method of calculating the [redacted] was taken directly from [redacted] In fact, [redacted] This [redacted] thus some adjustments had to be made. In order to [redacted] to be set to [redacted] This allowed the [redacted]

[redacted]

[redacted]

As desired with the [redacted] needs to be [redacted] and thus a [redacted]

4.2 *Computational Fluid Dynamics (CFD)*

SmartTruck System's TopKit was found to have a 9.07% improvement in drag.

	TopKit	Baseline	Difference
TRACTOR	0.333259	0.332230	0.001029
TRAILER	0.161495	0.211871	-0.050376
VEHICLE TOTAL	0.494754	0.544101	-0.049347
% DECREASE IN DRAG	9.07%		
% INCREASE IN MPG	6.06%		

Table 9 – CFD Results

A 9.07% improvement in drag results in a 6.06% improvement in highway MPG (at 65 mph). Raw data can be found in Appendix C – Computational Fluid Dynamics Data.

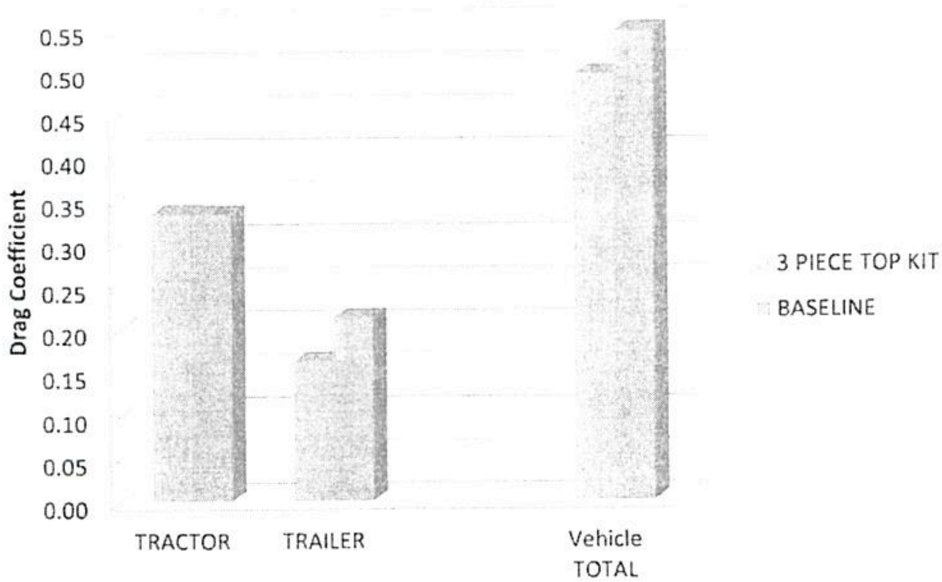


Figure 16 - Drag Coefficient Data

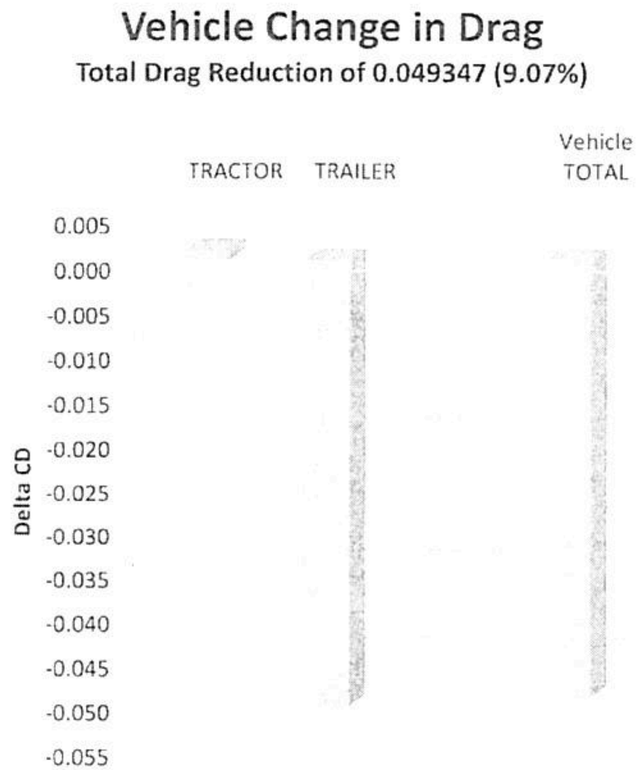


Figure 17 – Total Vehicle Change in CD

[redacted]

5 Summary of Results

5.1 Coastdown

	Avg. CD	% CD Decrease	% MPG Increase (65 MPH)
Baseline	0.61477	N/A	N/A
TopKit	0.56089	8.76%	5.95%

Table 10 - Summary of Coastdown Results

[redacted]

5.2 CFD

	Avg. CD	% CD Decrease	% MPG Increase (65 MPH)
Baseline	0.544101	N/A	N/A
TopKit	0.494754	9.07%	6.06%

Table 12 - Summary of CFD Results

6 Conclusion

The testing and data calculation protocols described in this document conclude that:

On today's most aerodynamic tractor trailer configurations, SmartTruck's TopKit System produces a 5.95% fuel efficiency improvement.

The TopKit System is expected to have slightly different performance with different types of trailers and tractors due to the differences in the aerodynamic performance of the base trailer and/or tractor. Additionally, different types of trailer and tractor components will also have a slight impact on the performance of the TopKit.

Preparation and Approval

Report Prepared By:

Date: 5-6-14

Nate See

Lead Test Engineer, SmartTruck Systems

Report Approved By:

Date: 5/6/14

Steve Wulff

Chief Operations Officer, SmartTruck Systems

Appendix A – Photos and Images

Images of the TopKit Trailer System

Figure 19 - Rear View of TopKit

Figure 20 - Side View of TopKit

Testing Equipment

[redacted]

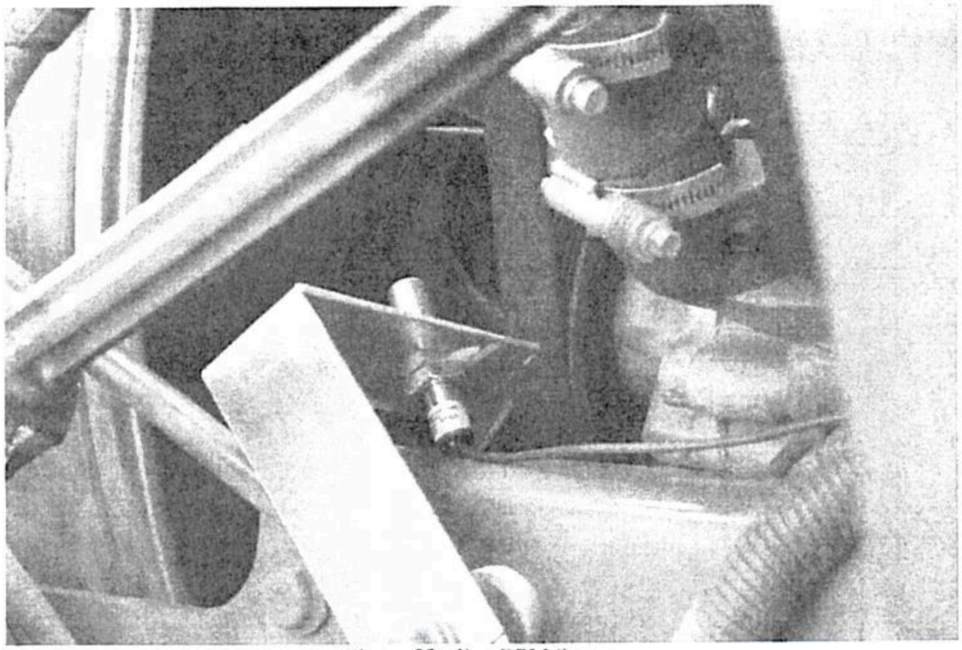


Figure 23 - Fan RPM Sensor

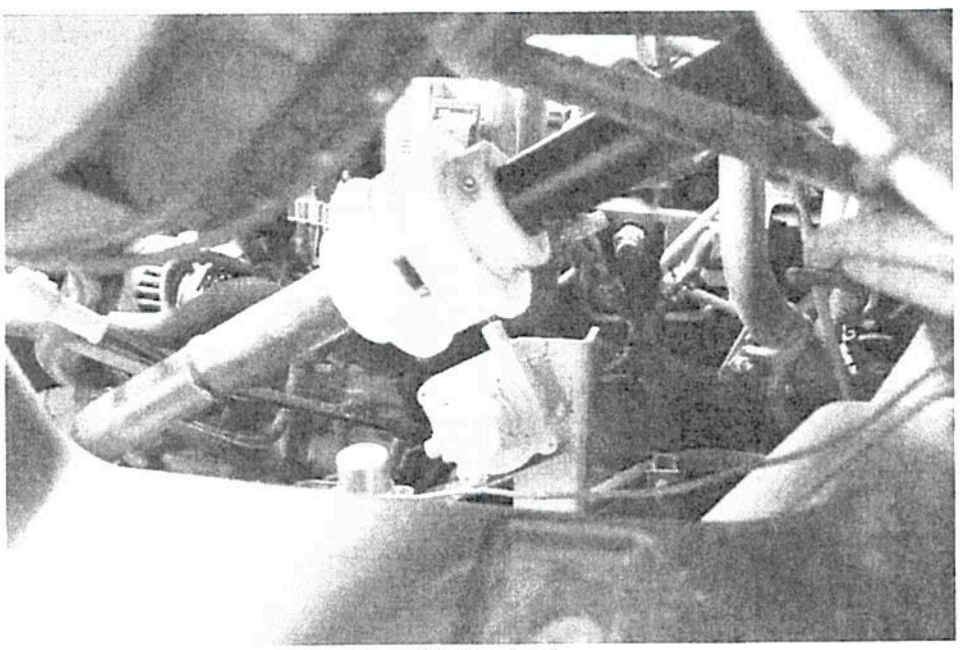


Figure 24 - Steering Sensor

Appendix B – Coastdown Plots

[redacted]

Figure 25 - TopKit Performances

Figure 26 - Live Density vs Time of Day

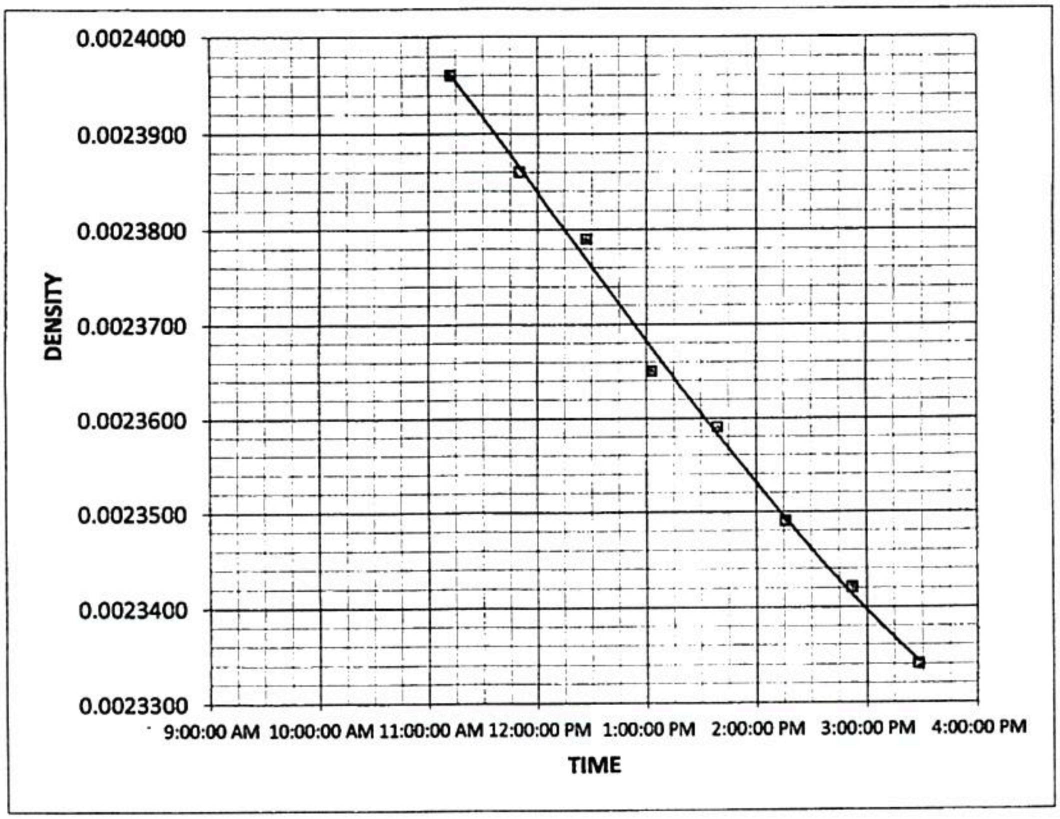


Figure 27 – Density Used vs Time of Day

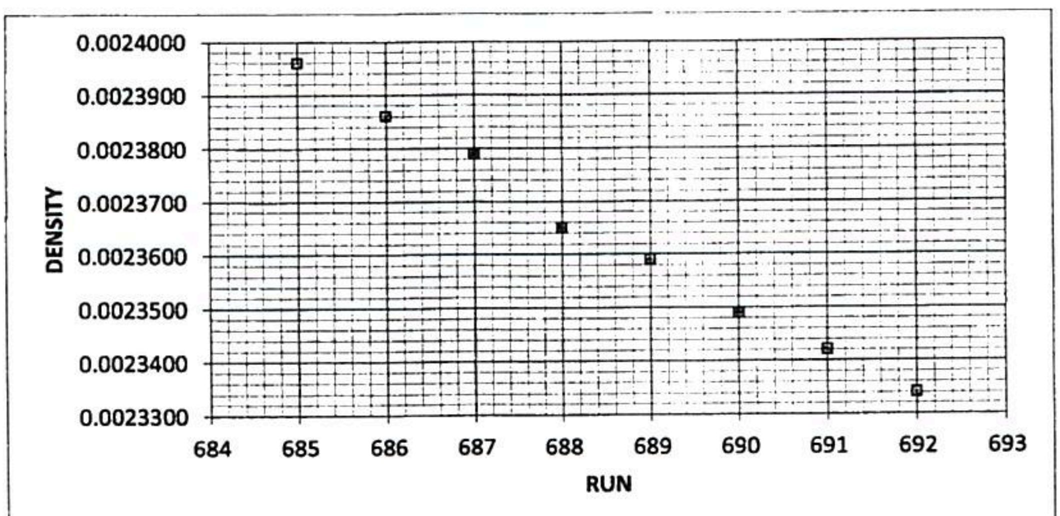


Figure 28 – Density Used vs Run Number

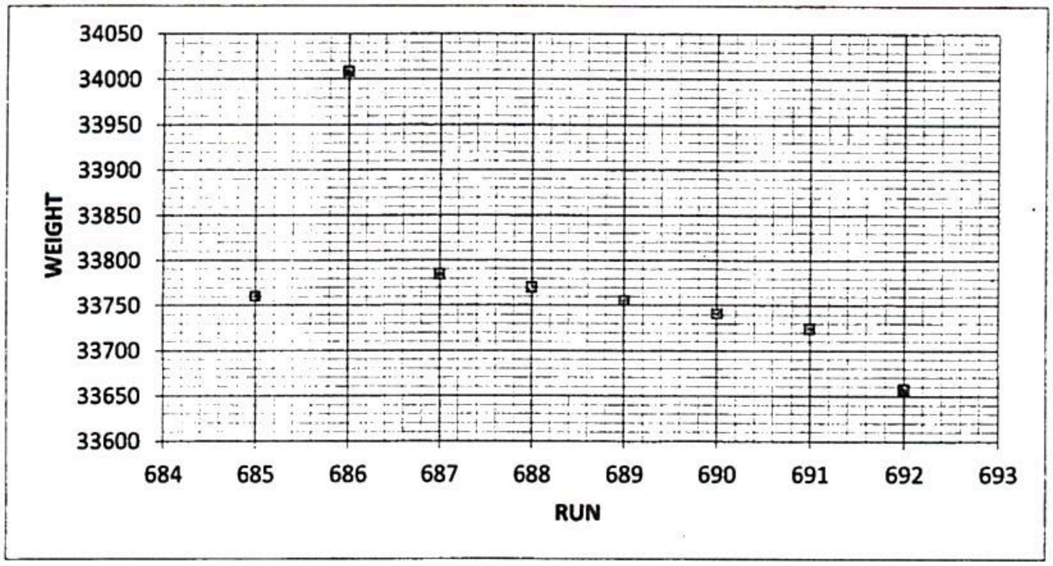
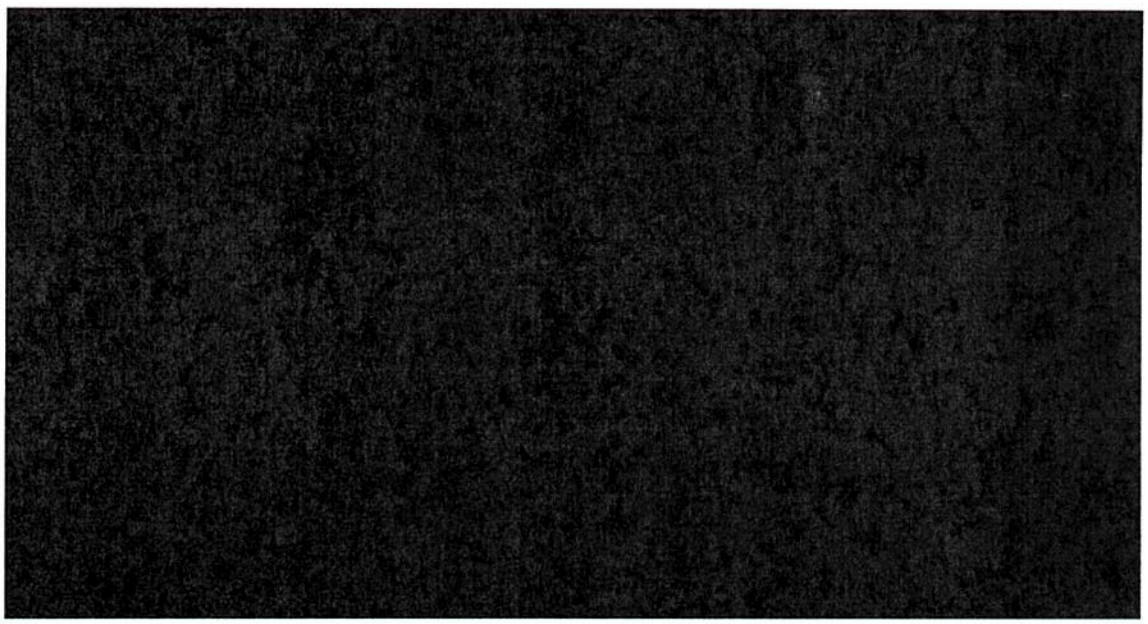


Figure 29 - Vehicle Weight vs Run Number



[redacted]

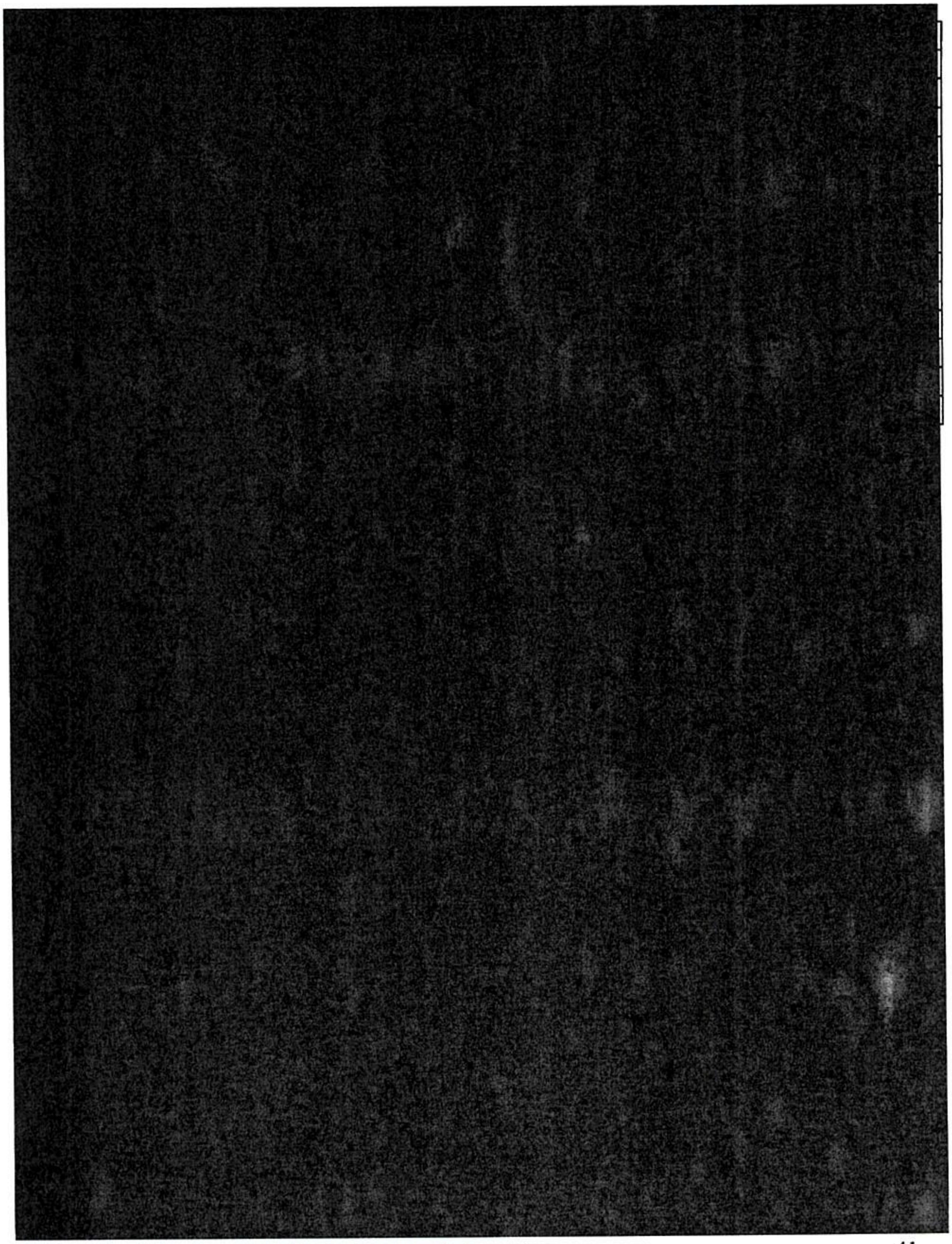
Figure 31 - CD vs Run of the Day

Appendix C – Computational Fluid Dynamics Data

Raw Data

[redacted]

[redacted]



[redacted]

Images from Computational Fluid Dynamics

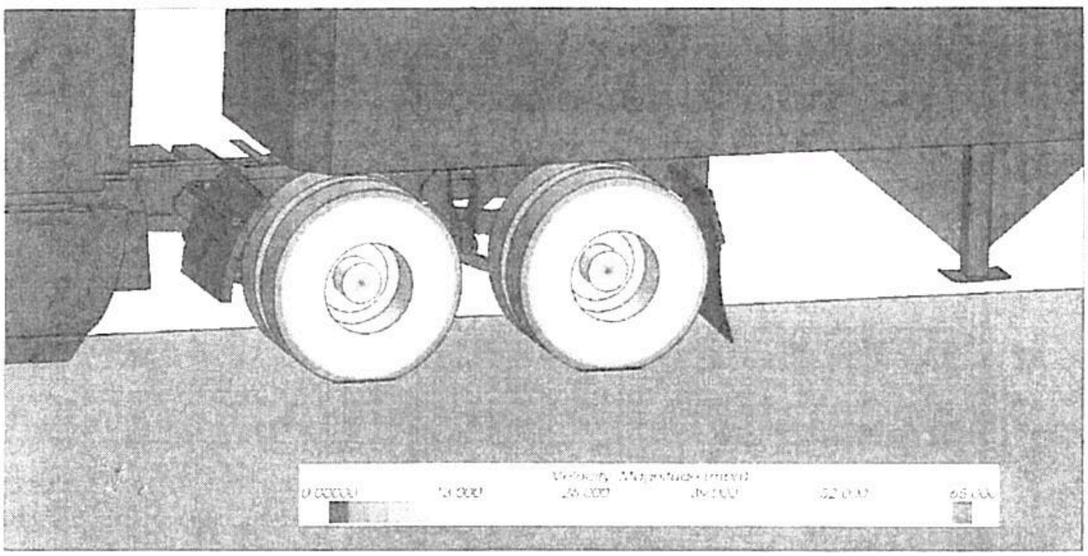


Figure 32 - Tire and Floor Velocity Boundary Conditions

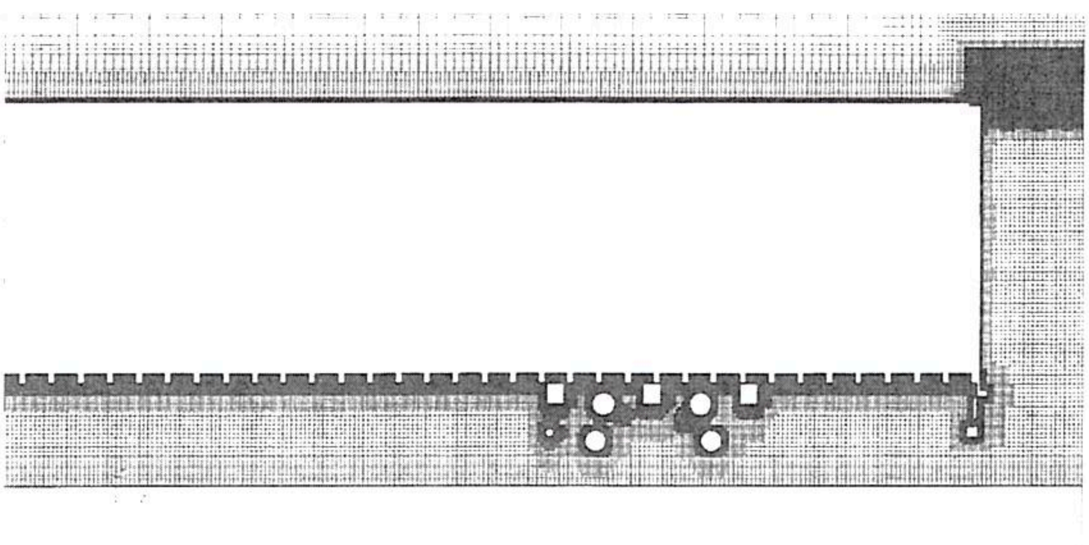


Figure 33 - Baseline Grid

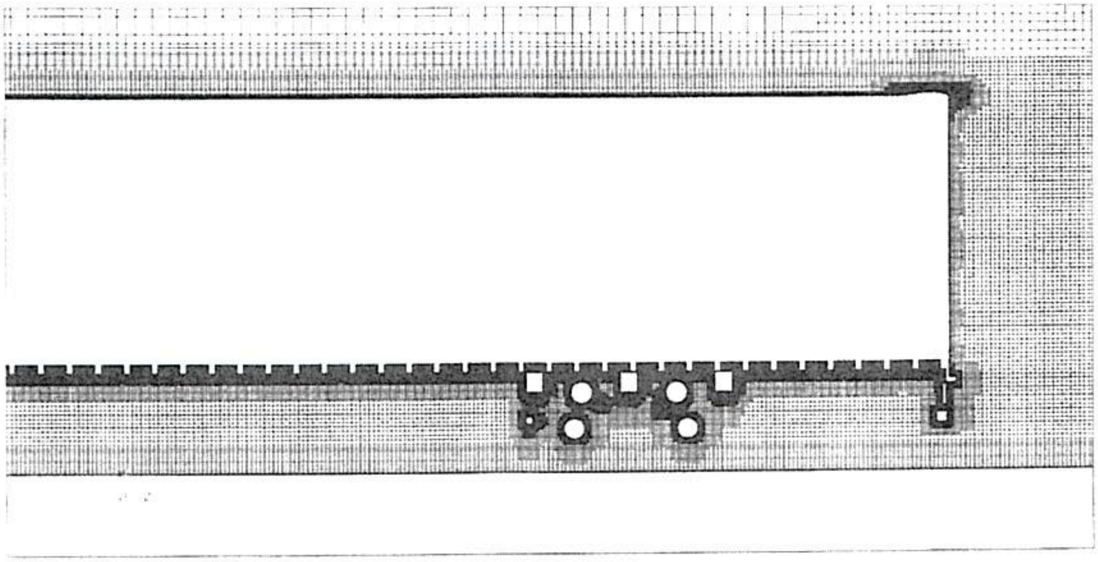


Figure 34 – TopKit Grid

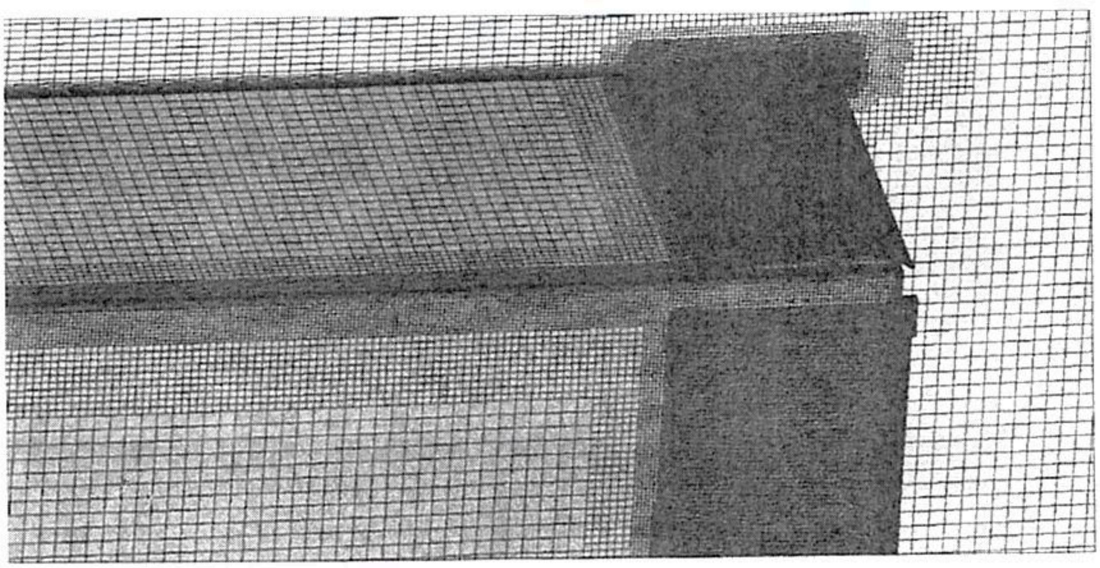


Figure 35 - TopKit Grid

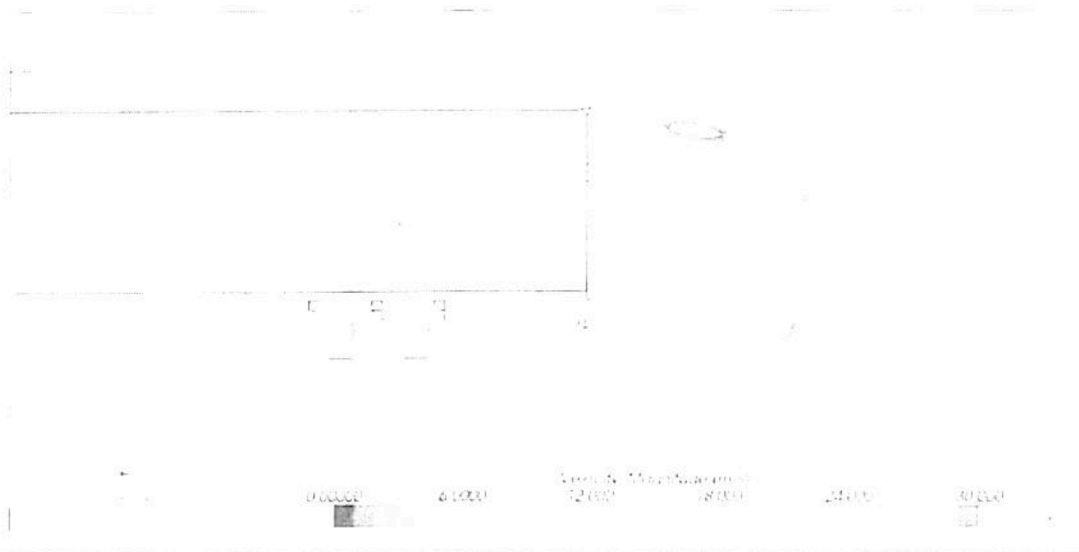


Figure 36 - Baseline Flow Visualization

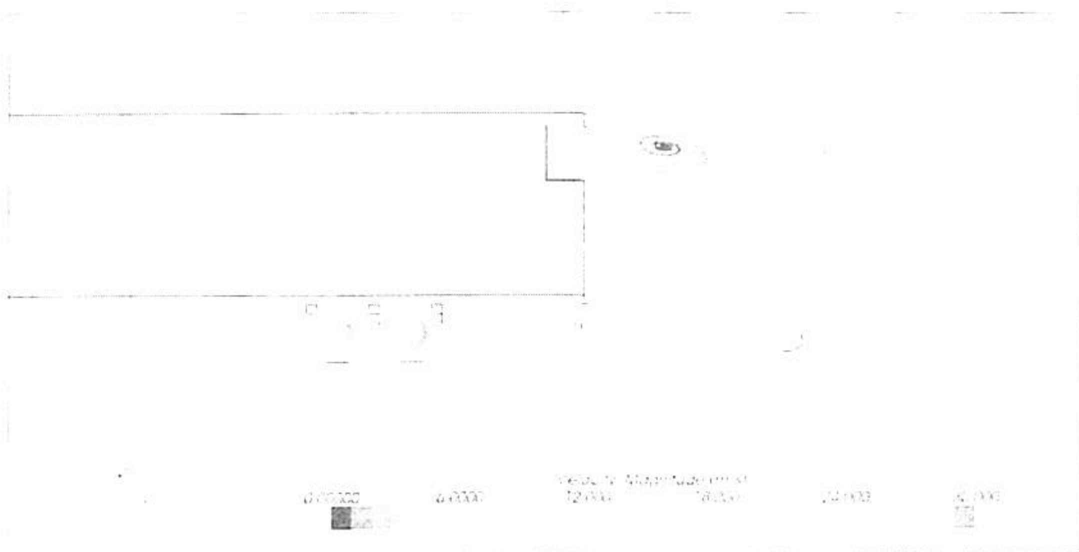


Figure 37 – TopKit Flow Visualization

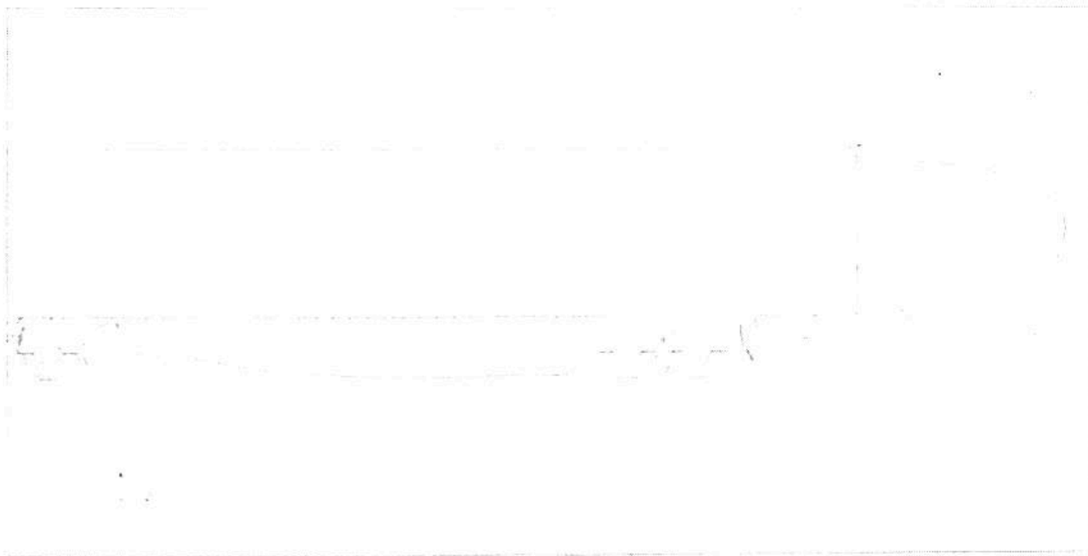


Figure 38 - Baseline Reverse Flow

Figure 39 – TopKit Reverse Flow

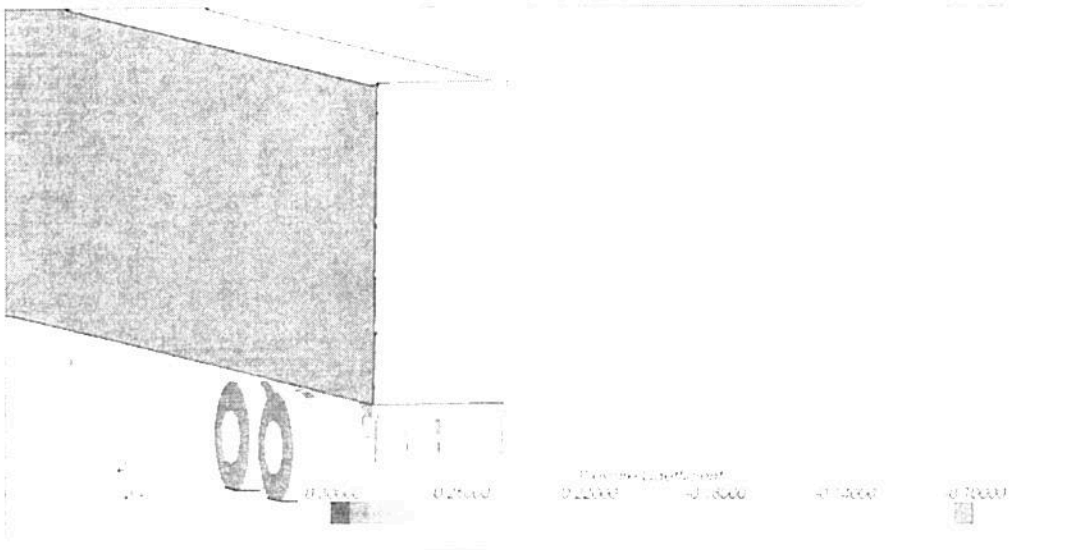


Figure 40 - Baseline Back Pressure

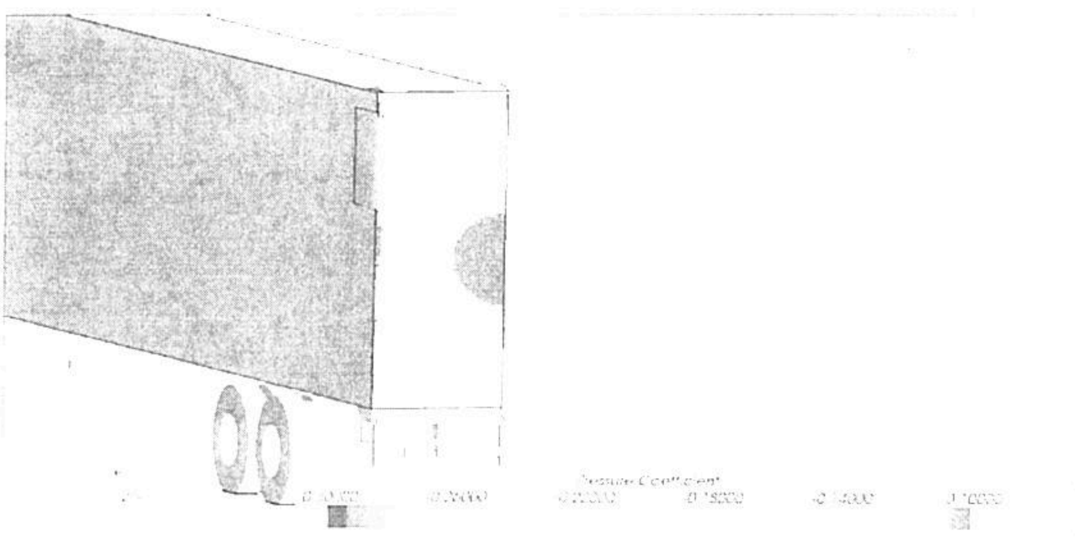


Figure 41 – TopKit Back Pressure